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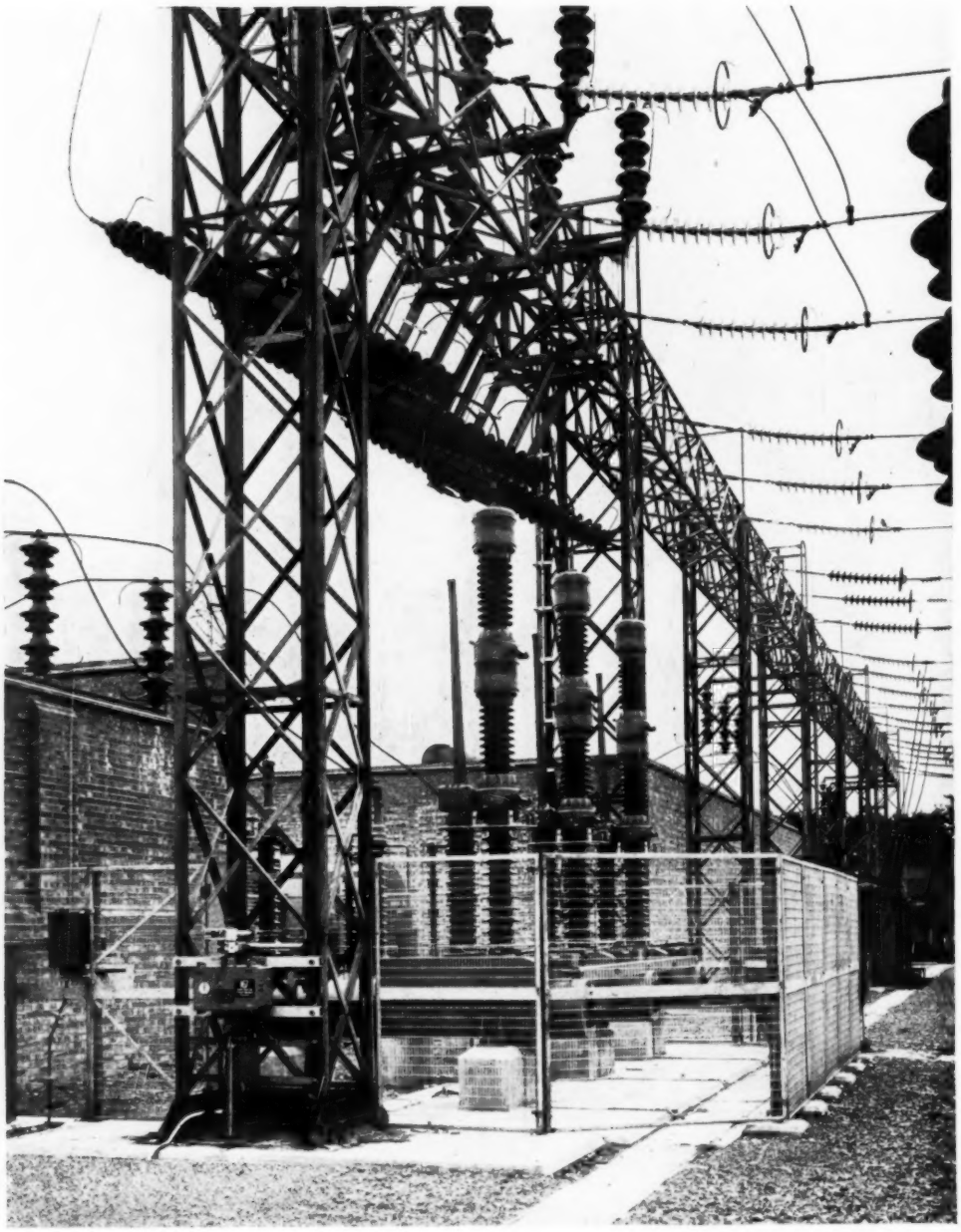

Outdoor air-blast circuit breaker in a 132 kV switching station. Bulk oil circuit breakers can be seen in the background.

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Vol XI. No. 1 JUNE, 1948. One Shilling

Some Observations on the Stressing of Major Parts of Traction Diesel Engines

By G. H. PAULIN, M.I.Mech.E., M.I.Mar.E., M.I.Loco.E.,
Chief Engineer, Internal Combustion Engine Department, Rugby.

This article is based on an address given by the author at a special meeting of the Rio de la Plata Branch of the Institution of Mechanical Engineers on 26th May, 1947, of which the chairman was Mr. E. I. Mayne, M.I.Mech.E., The English Electric Company's representative in Argentina, who was elected to the Chair for the session 1947-48.

A great deal has been said and written on the subject of internal combustion engines, and it is not proposed to refer to matters with which all mechanical engineers are familiar. There are some aspects of engine design, however, which do not usually come under review except in a design office, and reference to one or two of these may therefore be of interest.

In a modern multi-cylinder engine design the crankshaft is the most difficult component with which the designer has to deal. Numerous conflicting conditions control the ultimate form of the shaft and if these are not all dealt with adequately, satisfactory operation of the engine is unlikely.

A modern shaft should not fail if correctly designed and maintained. Failures are almost certainly due to two causes :—

(*a*) Torsional oscillation.
(*b*) Mal-alignment.

At this point it may perhaps be interesting to refer to the earlier days of the multi-cylinder engine. The stroke-bore ratio of the earlier engines was appreciably greater than is usually the case to-day. This resulted in shafts being much more flexible than the modern shafts. The earlier shafts, with cylinders usually not more than four in number and speeds only a fraction of those common to-day, did not suffer from acute torsional troubles, and mal-alignment did not have the disastrous effects it has in a modern engine. The diagram in Fig. 1 shows some factors involved in this comparison.

A further point of major importance is that the earlier true diesel engine operated on the constant pressure cycle, thus the maximum pressure in the cylinder was little above the value of the compression pressure. With the elimination of blast air injection the working cycle became quite different, and most modern airless injection engines operate on the constant volume cycle or a cycle approximating thereto. This means that a very considerable rise of pressure takes place on the injection of the fuel. It is common for

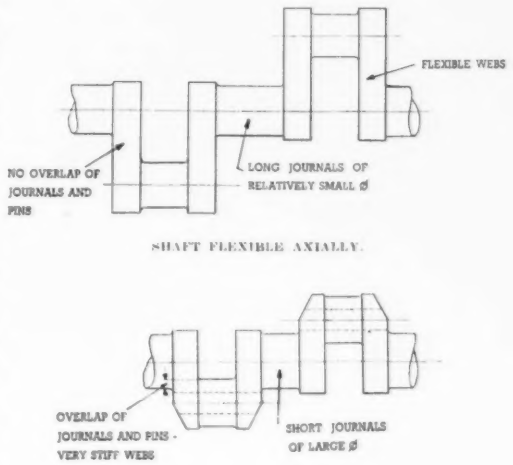

FLEXIBLE WEBS
NO OVERLAP OF JOURNALS AND PINS
LONG JOURNALS OF RELATIVELY SMALL Ø
SHAFT FLEXIBLE AXIALLY.
OVERLAP OF JOURNALS AND PINS - VERY STIFF WEBS
SHORT JOURNALS OF LARGE Ø
SHAFT VERY RIGID AXIALLY.

Fig. 1.—Diagrams comparing features of early and modern engine shafts.

this rise to amount to several hundreds of pounds per square inch. The conditions vary a little according to the speed of the engine and the form of combustion chambers but, in general, the airless injection engine in its operation does involve high cylinder pressures.

These higher pressures have a considerable influence on the torque curves and, of course, on the stress conditions in the crankshaft and structural portions of the engine—principally the crankcase. Taking firstly the torque conditions, these have a profound influence on the torsional conditions of the shaft system. In theory, a system composed of n masses with n-1 connecting shafts will have n-1 modes of vibration, corresponding to 1, 2, 3 . . . n-1 nodes in the shafting, as shown in Fig. 2. In practice, however, only the first few modes (usually only two in normal engine-generator sets) need be considered since the frequency of the others will be very high and will not be susceptible readily to excitation. The chief difficulty arises from the fact that there are exciting impulses of numerous frequencies, causing resonance at many different running speeds. The torque produced by any reciprocating engine is far from uniform, and this is particularly marked in the case of internal combustion engines—and most marked in the case of the oil engine with its heavier reciprocating parts and higher pressures.

The torque curve from any cylinder can be split up into a Fourier series of harmonics of progressively higher frequency, each of which will be in resonance with each vibration frequency at a particular speed. For instance, suppose that the fundamental natural frequency of the system is 4,000 cycles/minute, then, with a basis value of 4,000 c.p.m. the 1st, 2nd, 3rd . . . harmonics of the torque curve will tend to cause vibration

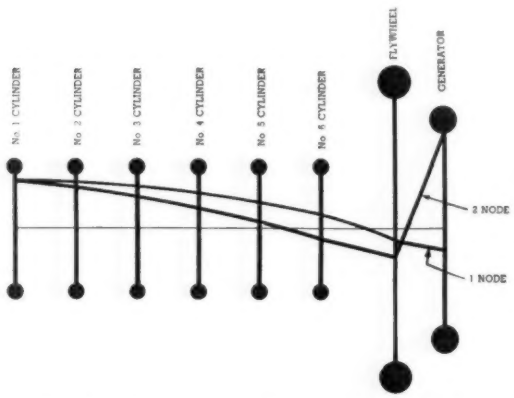


Fig. 2 —One and two-node vibration modes of typical engine-generator system.

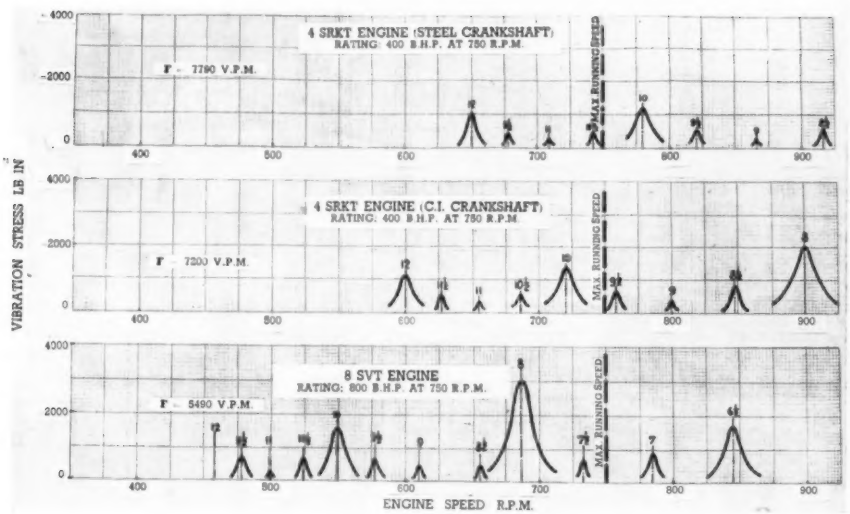
at 4,000, 2,000, 1,333 . . . r.p.m. respectively, these being called the critical speeds of the 1st, 2nd, 3rd . . . orders. Four-stroke engines will also have critical speeds of the $\frac{1}{2}$, $1\frac{1}{2}$, $2\frac{1}{2}$ . . . orders, since the complete torque cycle for one cylinder occupies two revolutions.

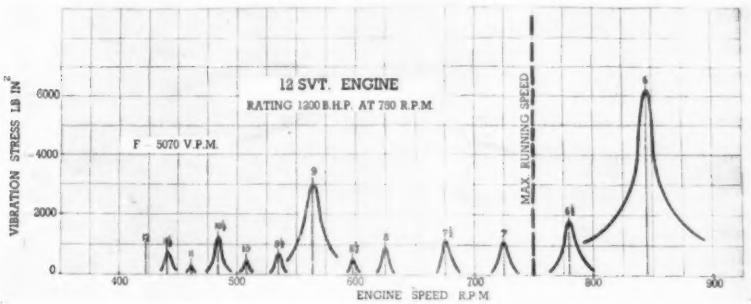
As stated earlier, the older types of internal combustion engines had usually only up to four cylinders, while the running speeds were low. In consequence, the critical speeds, or resonant zones, in the running range were of a relatively high order number, the corresponding torque harmonics being small. If, in these conditions, any vibration did occur, it was therefore small in amplitude.

When the number of cylinders began to increase and the rotational speeds to rise, this easy state of affairs, unfortunately, no longer applied. Designers were faced with new problems, some of great difficulty. Systematic research, together with mathematical investigation and much ingenious experimental work, has disposed of the difficulties, and it is now possible to design shafts which in practice will accord, within a very small percentage, with the mathematics of the design.

The designers ideal is to provide a shaft with a natural frequency such that the most serious critical speed will be above the maximum running speed. In the case of a 6-cylinder engine the 6th primary would be the critical mostly concerned, and in an engine with an operating speed of, say, 750 r.p.m., the location of the peak of the 6th resonant zone should be 12 per cent. to 15 per cent. above the running speed—say, at 850 r.p.m. The fundamental frequency of the shaft system meeting these requirements would be 5,100 c.p.m. The only other critical of any real importance in such an engine would be the 9th primary, and this would occur at 566 r.p.m. In any case, in this resonant zone, the induced stress at full build-up of amplitude with a shaft designed on this basis would be so low that operation on it would entail no danger or inconvenience. These conditions apply also to a Vee-type engine of 12 cylinders, the shaft having six crank throws, as in the case of the in-line engine. It is possible to design a 6-throw shaft in accordance with the foregoing, and all engines built by The English Electric Company are so designed.

Unfortunately, it is not generally possible to have such ideal conditions when the shaft contains more than six cranks. It will be apparent that in designing a range of engines it would be impracticable to have crankshafts with different journal sizes for engines with different numbers of cylinders. The usual practice is to design the shaft to give the best all-round conditions for the higher numbers of cylinders and to use the same scantlings, bearings, etc., throughout the whole


4 SRKT ENGINE (STEEL CRANKSHAFT)
RATING: 400 B.H.P. AT 750 R.P.M.
F = 7790 V.P.M.
4 SRKT ENGINE (C.I. CRANKSHAFT)
RATING: 400 B.H.P. AT 750 R.P.M.
F = 7200 V.P.M.
8 SVT ENGINE
RATING: 800 B.H.P. AT 750 R.P.M.
F = 5490 V.P.M.
MAX. RUNNING SPEED
VIBRATION STRESS LB IN²
ENGINE SPEED R.P.M.



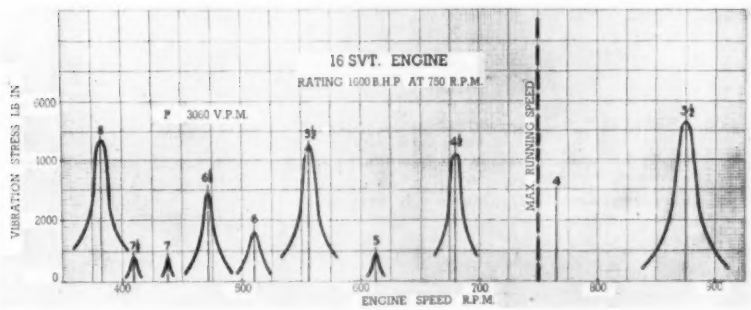


Fig. 3.—Spectra of crankshaft stresses due to torsional vibration for typical diesel-electric locomotive generator sets. (No Detuner). The vibration stress figures are positive and negative values.

range. In any case, to obtain the 8th primary above the running speed in an 8-throw shaft would involve journal diameters of an uneconomic size, together with reciprocating parts of undesirably light weight.

In the case of seven cranks, the 7th primary zone is below the running speed. In the case of eight cranks the 8th primary is below the running speed.

It is possible to have in a multi-cylinder engine a very high number of firing orders ; in the case of the seven-cylinder engine, for instance, the number amounts to several hundreds. The firing order has a direct influence on the torsional conditions and in the case of a 7-throw crankshaft (4 cycle) with firing order 1-3-5-7-6-4-2, the 7th primary critical comes well below the running speed and is the only major which needs mention.

In the case of the 8-throw shaft, in an in-line eight-cylinder engine, the only critical worthy of note is the 8th primary and this involves, with full build-up of vibration, a relatively low stress. In a Vee 16-cylinder engine with 45° angle of cylinder axes, the 8th primary comes in, together with the $4\frac{1}{2}$, $5\frac{1}{2}$ and $6\frac{1}{2}$, but none of these imply dangerous stresses—if the shaft system has been correctly designed. Fig. 3 shows the spectra of crankshaft stresses due to torsional vibration for typical diesel-electric locomotive generator sets without vibration dampers or detuners in the shaft system, as used for " English Electric " engines with 10 in. diameter cylinders.

It should be appreciated that to achieve fundamental frequencies of values sufficient to locate the 6th primary in a 6-throw shaft as described earlier, a large diameter is essential. The torsional stiffness of the shaft must be great and this also involves web design, although the journals are the greatest factor. The diameter of the shaft used for the engines to which Fig. 3 applies is 82.5 per cent. of the cylinder bore. Such a shaft entails a somewhat greater weight and cost, but this is of insignificance when assessed with the enormous advantages inherent in freedom from torsional vibration.

In a railway traction diesel engine, frequent variations in rotational speed are, of course, inevitable. This involves doubly frequent passage through resonant zones—as the speed rises and falls. To damp down the build-up of vibration amplitude during passage through the resonant zones, vibration dampers are used frequently. These dampers are more usually of the friction type and, even if force lubricated, wear takes place in the frictional surfaces. This inevitably means that the loci of the resonant zones is altered, which in itself may be dangerous, but in addition, the effect on the total build-up of vibration is prejudiced. The Company has used force-lubricated friction dampers with fair success, but there is no doubt about the weaknesses described. In order to endeavour to achieve complete damping of torsional vibration in a manner which would be permanent and non-variable, the Company has developed a detuning device which has no frictional effect. This device is, of course, attached to the free end of the shaft, and consists of fixed and free masses. The free masses are connected to the fixed mass through the medium of flat laminated springs radially disposed around the periphery of the circular discs which constitute the masses.

The action of this device is simple. In effect, the spring packs exert an opposing torque equal to the torque induced as torsional displacement of the shaft tries to build up during passage through the resonant zone. Some torsional displacement is of course inevitable in order to allow the spring packs to exert their influence. This displacement, however, is small, and of negligible value so far as shaft stresses are concerned. Fig. 4 shows the effect of the detuner on the 9th primary critical of a 12-cylinder 45° Vee engine. It will be noted that the resonant stresses are reduced from ±3,500 p.s.i. to ± 1,000 p.s.i. It is interesting to record that the vibration without the detuner could be just faintly detected orally. With the detuner it was quite impossible to detect any vibration. This was to be expected, as ±1,000 p.s.i. is quite negligible.

Reference has now been made to the manner in which satisfactory shaft stress conditions are obtained so far as torsional vibration is con-

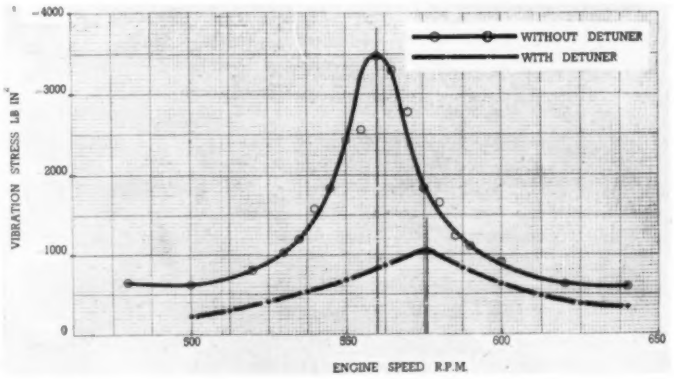


Fig. 4.—Measured crankshaft stresses in '12SV' type engine due to torsional vibration, shewing effect of detuner on 9th order " critical speed ".

cerned. It is, however, profitless to use a well-designed shaft in an engine which suffers from lack of rigidity. As shown in Fig. 1, the modern shaft is very stiff axially, and any deflection of the engine structure, however small, has a profound influence on the shaft stresses and bearing conditions.

In order to achieve the high-frequency values already referred to, the shaft must be kept as short as possible. The old ideas of long journals —sometimes ratios of $\frac{L}{D}=2$ or more were used— may have been more or less satisfactory with the engines to which they applied. In the modern engine, however, bearings with a ratio as low as $\frac{L}{D}=0.7$ are used. These bearings are highly satisfactory for reasons which will be apparent.

For satisfactory operation of such shafts the maximum rigidity of bearing mounting is absolutely essential. In some designs of engines—mostly the smaller oil engines and petrol engines—a suspended shaft is used. That is, a shaft which runs in bearings suspended from the lower portion of the crankcase, the caps usually being attached to the main structure by studs or stud bolts. In this arrangement a light sheet-steel or aluminium sump is bolted to the lower face of the crankcase to contain the lubricating oil.

A little consideration will show that the modulus of the section through such an arrangement of crankcase and sump is not high. As the number of cylinders is increased and the engine becomes longer, conditions become rapidly worse. The complete engine structure, unless the crankcase is a very deep one, can be relatively easily deflected. If such deflection takes place in operation, as experience shows is the case, and fine bearing clearances are used, the bearing caps are strained. This starts a vicious circle and ultimately it is probable that the whole bearing assembly will begin to breathe. Evidence of acute fretting seen on so many engines bears out that such conditions do arise in more or less severe form. Furthermore, it would seem logical to expect maintenance of bearings and shaft to be higher with such a design.

Conditions are made much worse when, as is sometimes the case, a shallow crankcase is used, with bolted-on cylinders. Here, the modulus of the section is very poor and longitudinal rigidity of a low order. It is improbable that an engine so constructed could give low maintenance or long service.

The English Electric Company has had a very extensive experience in railway traction. This experience is kept continually under survey—together with published data of the experience of other manufacturers long connected with railway work. There seems little doubt that if reliability is the criterion of the virtues of a railway traction oil engine, then there is a specific minimum engine weight which cannot be disregarded. It follows, that with reliability, low maintenance and other advantages are certain.

The engines designed and made by the Company always have the crankshaft carried in a rigid bedplate. Such a design need not be excessively heavy, and with the full-depth crankcase mounted on the bedplate and bolted firmly thereto, the section modulus is very great, resulting in an extremely rigid structure. As the bolting of the crankcase to the bedplate has to allow for the piston loading, the efficiency of the joint is high. In any case, the joint is approximately in the region of the neutral axis of the complete section.

Such a structure can be readily mounted on three points in the locomotive frame and this mounting eliminates all risk of straining due to deflection of the locomotive structure in working. The author has seen locomotives badly strained by serious derailment or collision. In all cases the diesel engine has escaped any damage. If the engines in these accidents had been bolted rigidly to the locomotive structure, serious damage would have been certain.

The mounting on three points is theoretically highly desirable. Not only does it provide the insurance against fortuitous straining as previously referred to, but it allows of virtual elimination of bending moments in the engine structure. Fig. 5 shows how, by locating the supporting points at suitable places, the overhanging weights at generator and free end induce negative moments which reduce the maximum bending moments to a low value.

Several hundred equipments constructed as described have been installed by The English Electric Company in locomotives and in war vessels. In no case has the three-point mounting given the slightest trouble. This is particularly

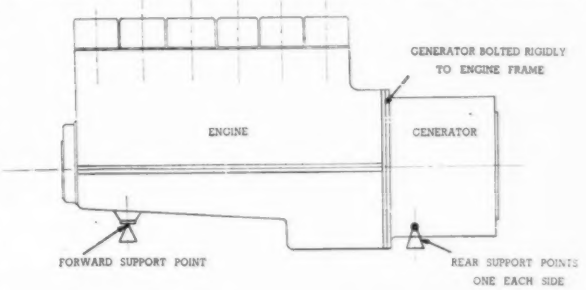


Fig 5.—Location of supporting points on 3-point mounted diesel engine generating set.

interesting when it is appreciated that many of the units were installed in destroyers or similar craft in which the motion in heavy weather is very violent. All such mountings were designed for insulation against under water explosions. Stresses resulting from accelerations equivalent to 20g and more had to be met.

A further interesting example was provided in the Middle East during the war. A standard shunting locomotive equipped by the Company was derailed by the blast from a heavy shell or a bomb. The locomotive rolled down an embankment and came to rest at an angle of 45°, standing partly on its roof. When the officer in charge hurried to the scene it was found that although serious damage had been sustained in other directions, the attachment of the engine and generator to the locomotive was unaffected, and the engine was still running. It was necessary to force an entrance to the locomotive casing in order to stop the engine.

A Wartime Rectifier Plant for the Electrolytic Production of Aluminium.

By K. D. PHILLIPS, B.Sc., A.M.I.E.E., Rectifier Substation Section, Stafford.

The article describes the largest rectifier station in Great Britain. The plant was manufactured by The English Electric Company, Ltd., to the order of the British Aluminium Co., Ltd., acting on behalf of the Ministry of Aircraft Production, and was installed at the Port Tennant Works, Swansea, where the rated output of 41,200 amperes at 675 volts was used in the manufacture of aluminium.

Duty.

The manufacture of aluminium generally starts from the ore bauxite, which is a hydrated aluminium oxide mixed with impurities. This ore is treated chemically until the aluminium oxide or alumina remains. Reduction of the alumina to the pure metal is carried out by electrolysis in the molten state and this is effected in carbon-lined steel cells with carbon anodes. Cryolite, a fluoride ore of aluminium, is used as a flux, and pure molten metal is deposited, beneath the mixture of cryolite and alumina, on the carbon cathode forming the cell bottom ; the metal is withdrawn periodically from the cell.

An economical and efficient cell takes a direct-currect of around 40,000 amperes, at which the required normal voltage is approximately five, and in order to utilise efficient plant for the power source 100 to 130 cells are connected in a single series or cell line. A cell line of this type is operated continuously at full load current, as a shut-down of a few hours would result in the contents of the cells "freezing." This would cause loss of production for many weeks while the solidified flux was removed with pneumatic drills and the cells were, if necessary, relined ; stand-by plant to permit maintenance work without shut-down is therefore essential.

During the initial commissioning period of the cells, considerable labour is involved, and to maintain the labour balance cells are brought into service consecutively in small groups. The power plant must consequently be able to deliver its full rated current from a low voltage right up to the maximum. Further voltage variation is required to enable individual cells to be by-passed and withdrawn from service for maintenance. In addition the voltage of a cell suddenly rises from 5 to around 30 if the cells becomes low in alumina content and in a line of 100 cells it is usual to cater for an average of one or two cells being in this condition continuously.

The high ratio of the power cost to the finished cost of the metal demands efficient power plant, and the choice of mercury arc rectifiers operating at 600 to 1,000 volts is automatic. In this case the plant output of 27,810 kW. demanded an input 24 hours a day of over 30,000 kVA, and the plant therefore had to be located in an area where this power could be made available and where transport facilities were available to handle the ore. At the Port Tennant Works, power at 33 kV, 3-phase, 50 cycles, could be taken directly from the Tir John Power Station busbars.

General Arrangement.

The arrangement of the plant in broad outline was determined by the number of rectifiers used. As 4,120 amperes is a convenient rating for a

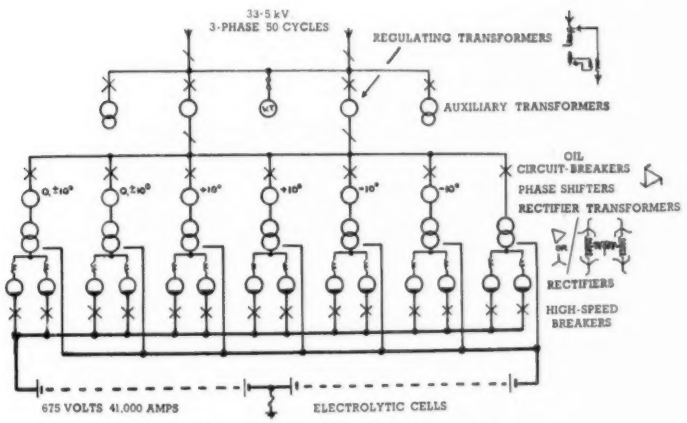


Fig. 1. Diagram of main connections.

single rectifier and 8,240 amperes for a single transformer, five pairs of rectifiers and five transformers were required and in addition a sixth pair and transformer as stand-by plant. A seventh pair of rectifiers and a transformer were installed as a further safeguard under war-time conditions, but this extra unit would not be necessary in any future plant of this nature.

The rectifier transformers are connected as shown in Fig. 1 to a common busbar fed from the incoming supply through one of two full-capacity regulating transformers having on-load and off-load tappings for voltage variation; further voltage variation is obtained by changing the primary windings of the rectifier transformers from delta to star or vice versa. These devices plus the use of grid control enable the D.C. voltage to be varied between 100-675 volts, assuming the A.C. supply to be within 95 to 100 per cent. of 33.5 kV.

33 kV Switchgear.

Fig. 2 gives a general view of the outdoor switchgear all mounted on reinforced concrete structures with liberal use of antiblast and anti-splinter walls. Type OKH4 single tank de-ion grid oil circuit-breakers having a breaking capacity of 750 MVA at 33 kV are uesd, but circuit-breakers on the output side of the regulating transformers were saved by the use of isolators which were made capable of breaking the magnetising current of these transformers so as to enable the changeover from one transformer to the other to be carried out without a shut-down. As duplicate full capacity cables from the power station could not be made available, no incoming line circuit-breakers are used, although for peace-time plants of this nature it is recommended that duplicate supplies be available and that consideration be given to busbar duplication. Protective measures include the use throughout of insulators rated at 55 kV, screening wires above the switchgear and the provision of Mulsifyre fire-fighting equipment. The insulator safety margin was designed to cater both for the effects of salt-laden fogs and for the slow removal of the glaze on the porcelains by the hydrofluoric acid deposited in wet weather owing to the release, under some conditions of cell operation, of minute quantities of fluorine gas; this latter effect had been observed at other aluminium factories and

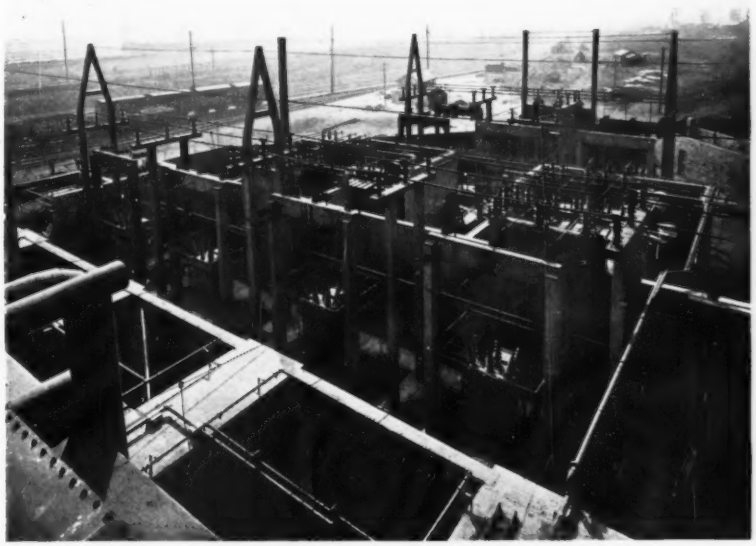


Fig. 2. General view of outdoor switchgear.

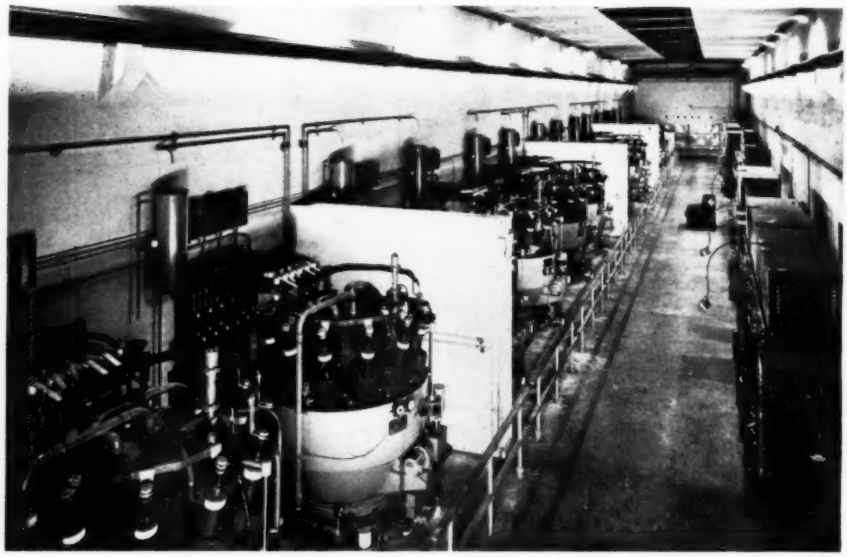


Fig. 3. The 12-anode pumped steel-tank rectifiers.

the application of protective coatings to the porcelains was under consideration during the war but was not actually carried out.

Transformers.

The regulating transformers each comprise two separate units, one being an auto transformer and the other a series bucking or boosting transformer. The auto transformer has an off-load tapping enabling the D.C. voltage to be reduced 25 per cent., and also an auxiliary winding fitted with an 18-step on-load tap-changer and feeding into the series unit so as to give 25 per cent. reduction in voltage on either auto transformer off-load tapping.

The rectifier transformers have twelve-phase secondary windings, as calculations showed that the fifth and seventh harmonics generated by six-phase operation of such a large installation would cause abnormal distortion of the A.C. supply waves with consequent risk of resonant effects and of interference with communications. Operating experience in fact indicated the necessity for even further phase multiplication as the thirteenth harmonic coincided with the resonant frequency of a capacitor/transformer combination used for power factor corrections some miles from the station, thus giving rise to excessive current in the capacitor. The possibilities of this occurring elsewhere decided the addition of a small phase-shifting auto transformer in series with each of six of the rectifier transformers and arranged to give the overall effect of 36-phase operation; under conditions of perfect balance the lowest harmonic generated is then the 35th, i.e., 1,750 cycles per second. The phase shifters give a displacement of 0°, plus 10°, or minus 10°, as appropriate, in the A.C. voltage applied to the rectifier transformers, and two have motor-operated phase-shift selector switches so that balanced 36-phase operation is obtainable with any one of the seven rectifier transformers disconnected.

The three interphase transformers associated with a 12-phase winding are mounted in each rectifier transformer tank which also contains the anode reactors necessary to ensure proper load sharing in the rectifiers, as two rectifier anodes are connected to each transformer phase.

Rectifiers and Auxiliaries.

Operation at full load current 24 hours a day is the worst possible duty for a rectifier, as the incidence of random backfiers—that is to say, backfires which occur for no observable reason such as overheating or bad vacuum or low temperature—is higher than when the same rectifier is operating on the usual intermittent industrial or traction loading, even if the r.m.s. loading is the same; in fact, backfires are very rare under these latter conditions. Rectifiers must therefore be derated for electrolytic duty and special care must be taken in their design and application to ensure that the backfire rate is small. A backfire, which is of course in effect a short circuit in a rectifier vessel on both the A.C. and D.C. systems, involves the automatic disconnection from the load of the rectifier

concerned, and on a plant of this nature does not so much represent a fault condition as an inherent characteristic of no particular importance ; research and development work tending towards the explanation and complete elimination of random backfires is, however, proceeding continually.

At the time the contract was placed, design work had just been completed on a pumped steel-tank rectifier of novel design as will be seen in Fig. 3. This 12-anode rectifier is fabricated throughout from relatively thin steel sheets, a construction peculiarly suitable for production in war-time ; further, the total weight of materials used is low owing to the rectifier being partly directly air-cooled. The rectifier fans draw air into the basement and through the water coolers ; the air is then discharged upwards inside the rectifier shrouds and through ventilators in the roof of the rectifier room. In cold weather the fresh air inlets are restricted and re-circulation is allowed inside the building. The cooling water is circulated, by a small centrifugal pump, through cooling chambers on the cathode and on the domed top and through annular coolers suspended inside the vacuum vessel. Direct air-cooling has the disadvantage of making the temperature of the rectifiers quickly responsive to changes in air temperature or load and while some measure of control is achieved by the use of automatic by-pass valves on the water coolers, the rectifier is basically designed for electrolytic duty and any other duty would demand the use of complex automatic air control systems.

The use of fabricated vessels with inserted anode arms permits the utilisation of a shorter arc path than is usual in a multi-anode steel tank of this rating, and in consequence a higher efficiency, the overall efficiency of the complete installation being 93.6 per cent. at the rated output. The construction of the vessels is also interesting, inasmuch as the whole assembly is permanently jointed together with the exception of the cathode assembly and the ignition anode assembly, both of which are jointed to the main tank via porcelain insulators and rubber rings ; all other electrodes are held by porcelain insulators soldered into steel cups. The soldered vacuum seal has been a feature of " English Electric " rectifiers for the last 10 years and has been used in many hundreds of permanently-sealed steel rectifier bulbs. The use of demountable seals for the cathode of a large rectifier eases constructional problems and also makes the interior readily accessible for overall. On each vessel the usual combination of mercury vapour pump and rotary vacuum pump is provided and these pumps are run continuously to deal with the gradual leakage of air at bolted joints and to ensure consistently reliable operation by maintaining a good vacuum (a pressure of one-thousandth of a millimeter of mercury, or less) under all conditions of loading and temperature. The small quantity of water required by the mercury vapour pumps is drawn from the mains as the temperature of the rectifier cooling water is too high for efficient pump operation. In the event of failure of the mains supply, operation is carried on by circulating water through a large storage tank on the roof.

Grid control of the rectifiers is used both for backfire protection and for voltage variation. Under backfiring conditions, detected by current transformers in the supply to the transformer concerned, a heavy negative bias, relative to the cathode, is applied to the grids of the pair of rectifiers by means of a high-speed relay ; the fault current derived from the A.C. system is thus suppressed in from one-half to one cycle after the start of the backfire. The reverse direct-current from the cells and from other rectifiers is interrupted by the high-speed breaker in the cathode lead of the rectifier concerned.

The apparatus for voltage control comprises essentially a small transformer for each grid phase fed through a wave distorter having a current output of triangular wave shape and of sufficient magnitude to saturate the transformer. Sharp voltage impulses are generated at each flux reversal and the positive voltage impulses are used to overcome the normal negative bias at appropriate instants. Variation of the grid

Fig. 4.—D.C. Switchgear in the basement.

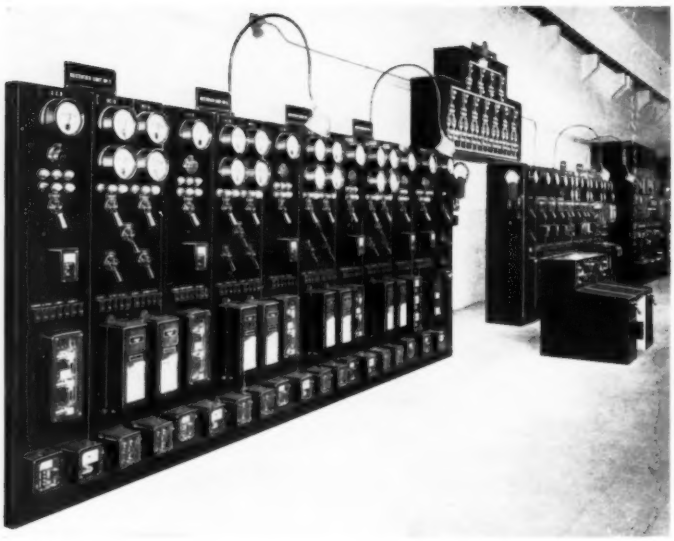


Fig. 5.—Main control board with mimic diagram.

impulse phasing is obtained, to a limited extent for balancing the load on individual rectifiers, by varying a direct-current through an auxiliary winding on each impulse transformer. Variation is effected on all rectifiers simultaneously by the use of a motor-operated phase-shifter (similar in construction to an induction regulator) connected in the common supply to all the sets of grid impulse transformers.

D.C. Switchgear.

The cathode circuit-breakers together with the busbars and isolators are mounted in the basement, as shown in Fig. 4, which also shows the rectifier coolers. These type OBX4 reverse current high-speed breakers were designed to clear severe faults, in view of the unusually large concentration of D.C. plant. The D.C. gear also includes a direct-current transformer mounted on one of the main 40,000 ampere busbars and comprising two cores around the bar, each with an A.C. winding; instruments connected in the A.C. circuits give a close approximation to the total D.C. output. More accurate metering is obtained by means of an electrolytic ampere-hour meter provided for each rectifier by the British Aluminium Company.

Control Gear.

Fig. 5 shows the main control board with mimic diagram and control desk in the centre of the rectifier room. The controls for the A.C. and D.C. circuit-breakers and the voltage of each unit comprising a transformer and a pair of rectifiers are grouped together to facilitate the switching in and out of individual units, whereas the controls for the regulating transformers and their circuit-breakers are grouped near the centre together with the A.C. metering equipment and the D.C. busbar ammeter and voltmeter. The control desk faces a gap in the control board behind which is a bay window overlooking the cell room; the desk contains controls for the grid phase-shifter and for the tap-changers together with a constant-current control relay.

The apparatus also includes two 1,500 kVA transformers to provide low-voltage power for the rectifier auxiliaries and the aluminium works, a low-voltage A.C. switchboard and fuse-switchgear, a battery and chargers, a bake-out transformer and resistances and earth leakage indicator and recorder for the mid-point of the cell line, arranged to shut down the plant on the occurrence of excessive earth current.

Operating Experience.

The plant was put into service in December, 1941, and operated until January, 1944, when it was shut down on Government orders which it is assumed arose out of the shortage of generating plant and coal and the build up of considerable aluminium manufacturing capacity in Canada using cheaper hydro-electric power. During the period of service the plant operated satisfactorily and produced around 12,000 tons of aluminium per year for the use of the Ministry of Aircraft Production. The longest shut-down, of five hours, was caused by the failure of a cable box at the power station, and several shorter shut-downs were caused by system disturbances due to barrage balloon cables contacting "grid" lines. The rectifier backfire rate, after the initial starting up period, was 0.6 per vessel per month and even this low rate was decreasing when the plant was shut down. The D.C. circuit-breakers were entirely satisfactory and the speed of operation was such as to limit the reverse current to a single rectifier to an estimated 30,000 to 50,000 amperes. This speed, coupled with the successful operation of the rectifier arc suppression equipment, ensured that a backfire only caused isolation of the rectifier concerned.

On a plant of this nature it is desirable to limit the use of grid voltage control to the smallest possible amount, preferably one or two per cent. except for the initial cell commissioning period lasting a few weeks, so as to limit the A.C. wave distortion. Voltage control, therefore, should, as far as possible, be carried out by on-load tap-changers ; this also has the effect of keeping the power factor high and of reducing the commutating voltage stresses on the rectifiers. On this plant it was hoped to achieve automatic constant current control, mainly by means of the on-load tap-changers but with grid control between taps. Automatic control was, however, found to be impracticable as the severe and frequent variations in the resistance of the cells were such as to make several thousands of control operations necessary each day so that maintenance work on any type of control mechanism would have been heavy. The plant was therefore operated at nominally constant voltage with hand control only.

Conclusion.

The design, manufacture and operation of this plant provided a fund of experience which could have been obtained in no other way. Further developments in the design of rectifiers and other apparatus, however, are such that identical apparatus would not necessarily be used for future installations.

The English Electric Company is indebted to the Ministry of Supply and to the British Aluminium Company for permission to publish this information and to reproduce the photographs herein, and also for the close collaboration of The British Aluminium Company's Engineers in the production of this plant.

Switchgear for Power Stations.

Choice of Type of Installation, Trends in Design, and a Note on Automatic Reclosing of Circuit Breakers.

By J. A. F. HARVEY, A.M.I.Mech.E., A.M.I.E.E., Deputy Chief Engineer, Switchgear Department.

This subject can be broadly divided into three main groups, namely :—

1. Switchgear for auxiliaries.
2. Equipment for switching at generated voltage.
3. Equipment for switching at transmission or distribution voltage.

Power Station Auxiliaries.

In modern power stations there are many supplies and services required which are preferably driven by electric motors. Many of these of course are associated directly with the operation of the main plant such as the coal pulverising mills, forced and induced draught fans, the feed pumps, the ash pumps, etc., for the boilers ; others are connected with the operation of the turbines and generators such as circulating water pumps for the condensers, oil pumps for the bearings, etc. In addition to these services which are driven by electric motors there are the general electric supplies required in such an establishment. The control of the electric motors driving the services and the circuits providing the supplies requires an extensive installation of switchgear. The horsepower of the motors varies considerably and some of large h.p. are found to be convenient and economical when designed for operation on 3,300 volts. Others of smaller h.p. are generally connected to 440 volts, 3-phase circuits. The supplies for the establishment vary in their duty and the larger circuits are controlled by circuit-breakers, whilst smaller ones are controlled either by contactors protected by high-rupturing capacity fuses or alternatively manually operated combination fuse-switch boards. Motors for use in a modern station are designed to be started direct-on to the power supply and in order to give suitable reliability and flexibility the circuit-breakers which control these motors are required to give a high standard of performance with reasonable maintenance under this condition of operation.

Many years of intensive study of the performance of arcs in air has led to the satisfactory development of air-break circuit-breakers which perform this rigorous duty very efficiently. Since high power testing stations have been at the disposal of the designers much work has been done on the design of arc chutes which are capable of satisfactorily splitting and de-ionising the arc in air, thus making it possible to produce a satisfactory air circuit-breaker for the short-circuit duty required in a situation of such close proximity to the generators.

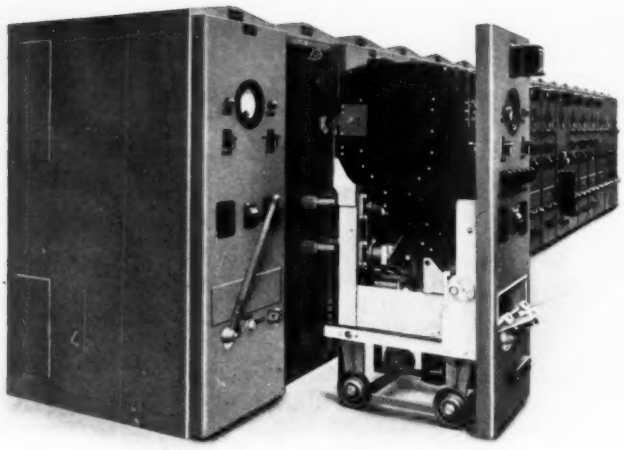


Fig. 1.—3,300-volt withdrawable truck-type circuit breaker equipments for controlling the larger power station motors.

Power station auxiliary demands up to now have required circuit-breakers only up to 3,300 volts and the air circuit-breaker has been developed in this country only up to that voltage. In America, however, air-break circuit-breakers are available up to 15,000 volts and 500 MVA American rating.

The development of the air-break circuit-breakers is not completed with the achievement of satisfactory arc chutes. It has entailed extensive research into the performance of contacts not only for providing in an economic space a contact which will carry an adequate full load current but also an auxiliary set of contacts which will not deteriorate severely when subjected to making and breaking fault currents, thus protecting the main contacts from damage. The advantage which the air-break circuit-breaker possesses in relation to the oil circuit-breaker as regards contact deterioration is that an arc in air is very much more mobile than an arc in oil and can be readily moved away from the contacts into the chute without doing much damage to the contacts, whereas in the oil circuit-breaker the arc is restricted in its movement by the inertia of the oil which surrounds it, and is inclined to cause bad "blotching" on the contacts. From the above it will be appreciated that air circuit-breakers give a better performance than oil circuit-breakers when subjected to a rigorous duty of switching direct-on started motors. The air circuit-breaker, in that it has no fire-hazard in this respect, is eminently suitable for power station duty. If oil circuit-breakers were used, extensive fire fighting equipment would also have to be installed to guard against possible serious outbreaks of fire. Other advantages of the air-break circuit-breaker include cleanliness of operation and maintenance and also ease of inspection and maintenance, which all indicate the reasons for many power stations in this country and abroad being equipped with this type of circuit-breaker for controlling auxiliary equipment.

Equipment for Switching at Generated Voltage.

The present-day voltage of generation is usually 11,000 to 15,000 volts, and in cases where power stations are required to generate and transmit their power away from the locality of the station, having no need to consider a local supply, the generator designer has it in his own hands to

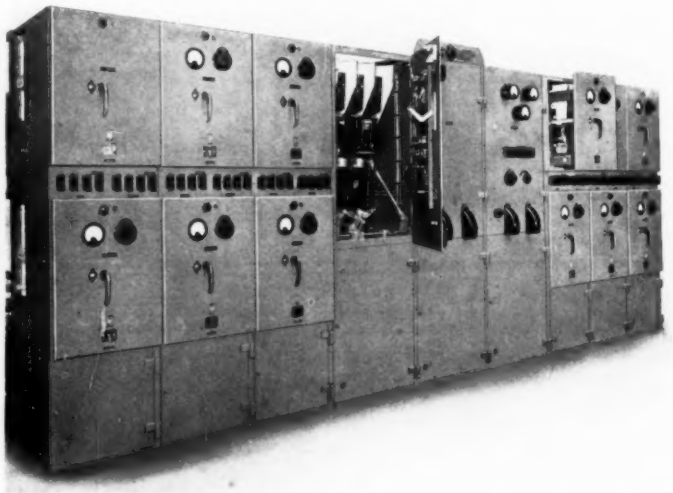


Fig. 2.—Composite switchboard of 440-volt circuit breakers, comprising large incoming breakers and smaller feeder breakers; the latter are assembled in double-tier formation.

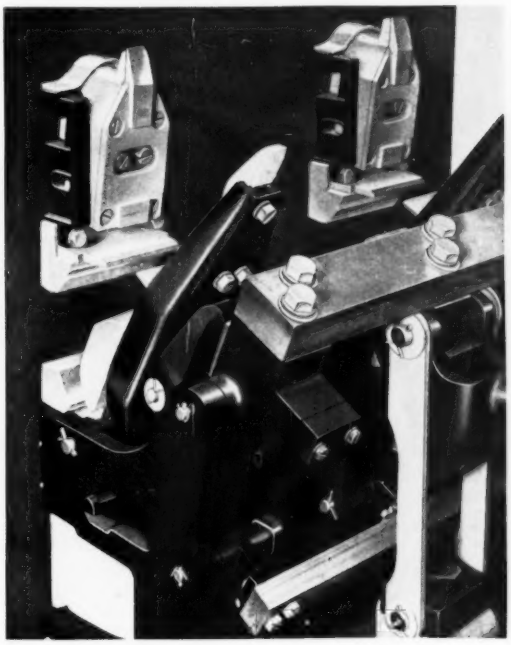


Fig. 3.—Contact system of air-break circuit breaker.

decide the best voltage for generation, as usually the generator coupled with a transformer forms the unit source of supply which is connected to high-voltage busbars where the switching is performed. When an appreciable local load has to be supplied then it is probable that the generator designer will have to provide a unit to generate at a standard voltage of 11,000 volts or 6,600 volts and in this case there will be busbars at this voltage to which the various generators in the station will be connected and from which the power will be fed to the local load, and in addition probably through step-up transformers to transmission lines. In the case of modern stations where the capacity for generation is high then the fault rating of the breakers which control the generators and feeders and are connected to the busbars will require to be in the order of 500, 750 or even 1,000 MVA. When making the choice of the switchgear for such an installation it is always an advantage wherever possible to instal switchgear indoors and, at such a comparatively low voltage, switchgear is available as factory assembled units, either of the metalclad filled construction or of the sheet-steel air-insulated construction. This type of unit takes up the minimum of space and, up to the present, requirements have been satisfied mainly by metalclad filled units employing oil circuit-breakers. It is quite evident, however, that air-blast breakers have become serious competitors to the oil breakers previously used, and the former will be supplied as factory assembled sheet-steel air-insulated units or alternatively they can be supplied for installation in a building of cell construction or again for comparatively small power installations they can be supplied in a truck unit withdrawable for isolation and inspection. These will bring all the advantages of air-blast switchgear in factory assembled units, and for many ratings may even show a saving over oil circuit-breakers on the building dimensions as well as on the floors and foundations, oil sumps and fire prevention equipment. The trend at the moment, however, is to avoid busbars at generated voltage if at all possible due to the heavy fault currents which are incurred, but economics usually dictate how a local load is to be supplied depending upon its size, i.e., in some cases it may be found economic to step down again from the high-voltage busbars in order to avoid say, 11,000-volt busbars.

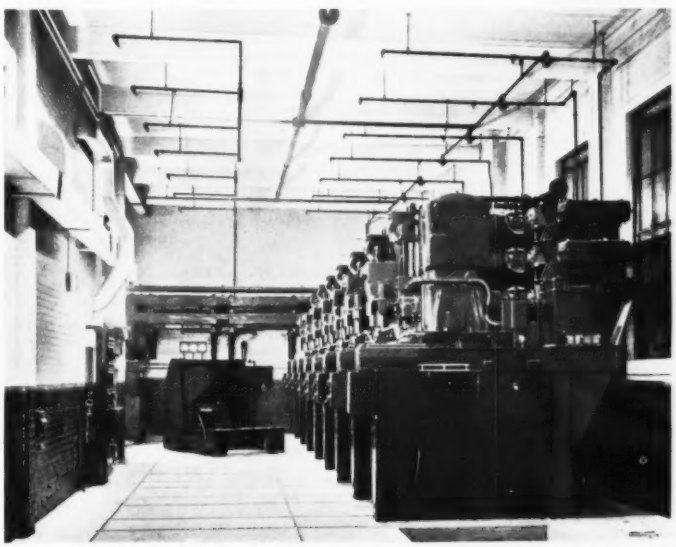


Fig. 4.—Metalclad-filled units employing oil circuit breakers.

Fig. 5.—Air-blast circuit breakers in cells.

Equipment for Switching at Transmission or Distribution Voltage.

When the immediately local load is not great the switching voltage is chosen depending upon the area to be served or the distance the power is to be transmitted. If a moderate size area is to be served, say, 1,000 to 4,000 square miles, then 33,000 volts has been chosen in many cases. At this voltage again installations are located indoors if economically possible; usually in the past compound filled metal-clad oil circuit-breakers were employed, but more commonly to-day the cellular construction with air-blast circuit-breakers is used. A compromise arrangement has also been installed in which the air-blast breakers are in brick houses with their local control gear, and busbars, isolators, etc., are of the usual outdoor construction. This gives the desirable feature of having the circuit-breaker indoors and is economically very favourable considering the features it offers.

Outdoor breakers, oil and air blast, are available for 33 kV., but it will be appreciated from what has been said previously herein, that their use is generally confined to substations.

Where power is to be transmitted over long distances, 66 kV, 132 kV, or higher may be chosen, in which case the switching stations are almost invariably of the outdoor type owing to the clearances and large proportions of the building that would be required for indoor installations. There are some stations, however, where at 66 kV the compromise arrangement has been chosen, with circuit-breakers in brick houses and the busbars and isolators outside. At 132 kV also, one or two trial indoor installations have been put into service with indoor type air-blast breakers.

At the transmission voltages the outdoor air-blast breaker is already establishing itself, although for a time the oil breakers, either bulk or minimum oil, may be in some demand for certain climates and conditions. The oil breaker is found to be still economically suitable for substations where only one breaker is required, as it does not need the auxiliaries of the air-blast breaker and may well be spring operated with a winding motor requiring only a small A.C. supply.

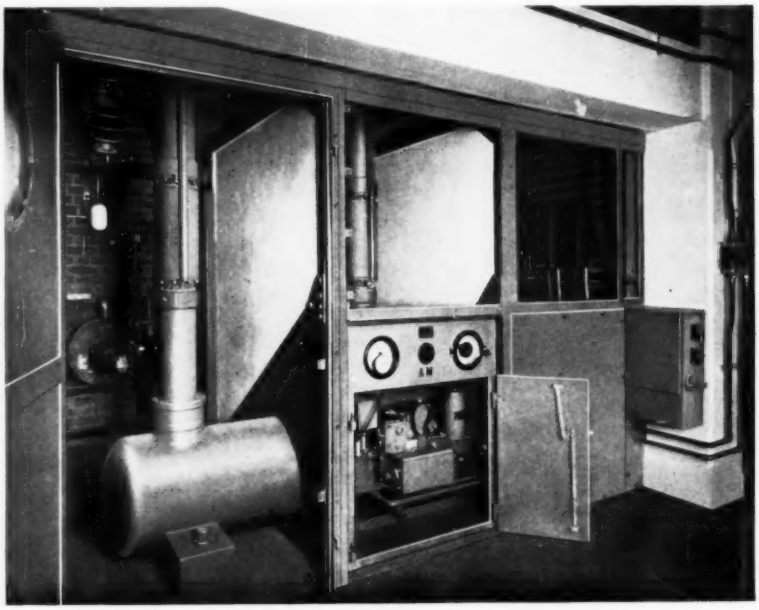


Fig. 6.—Detailed construction of cell showing air-blast circuit breaker and phase barriers.

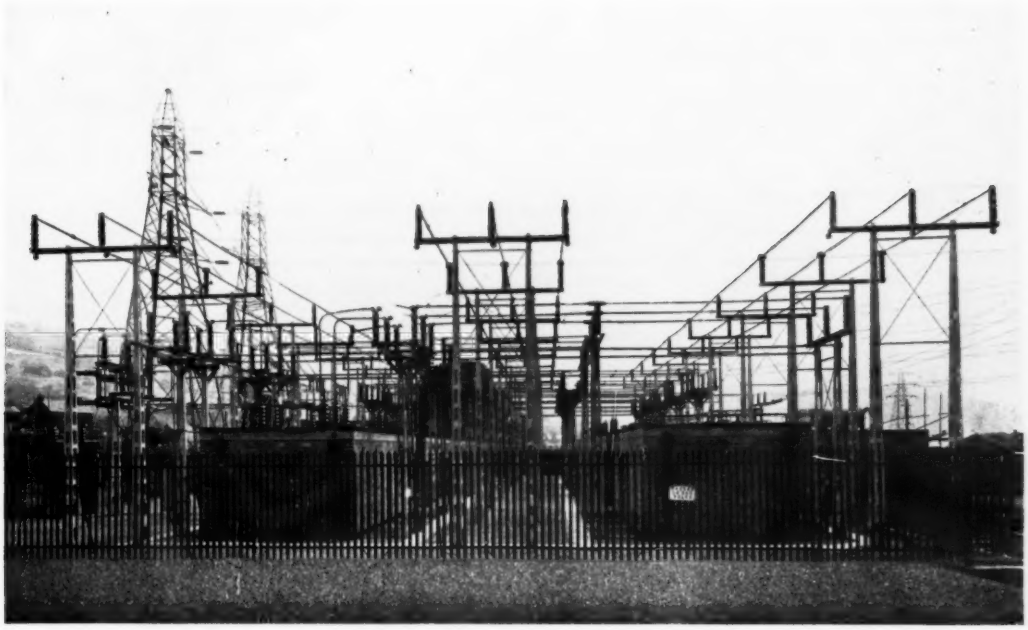


Fig. 7.—66 kV Switching station with outdoor busbars and isolators, and air-blast circuit breakers in brick houses.

MODERN TRENDS IN CIRCUIT-BREAKER DESIGN.

Oil Circuit-Breakers.

In view of the knowledge gained from the testing stations in the last 10 to 15 years, the trend in the design of oil circuit-breakers is towards the reduction of oil quantity, materials and thus weight. Much time and effort combined with costly plant have been used to determine just how economically one can design with suitable safety margins, and the results achieved have been most encouraging. The main contributions have resulted from careful study of the performance of arc control devices and their supports, and also of the forces in the operating mechanism, and the development of automatic making current releases or force trips. The force trip is a device which will rapidly release the circuit-breaker to open if, when closing, a fault current flows thus setting up a severe magnetic resistance tending to prevent the closing mechanism latching home in the fully closed position. With this device it will be seen that certain parts of the closing mechanism need not be so powerful or robust, and what is very important (in view of the fact that the closing mechanism is not required to be powerful enough to close the breaker when fault current is flowing) the moving portions are not subjected to such heavy wear and shock as previously whilst operating on normal service.

By the foregoing means reductions in oil quantity and material are achieved for a given rating by raising to this rating a smaller frame size than used hitherto, or, when designing new units, by using in addition all the experience available at present.

With the improvement in the performance of arc control devices and the reduction of arcing time, high-speed trip catches have also been developed for use with high-speed protection, and means are available for high-speed auto-reclosing. The latter two points will be appreciated after reading the section on auto-reclosing on page 19.

Designs for drastically reducing the oil content of units were being seriously contemplated six or seven years ago, before the potentialities of the air-blast breaker were fully realised, but it is only at the very high voltages, say, 110 kV and 132 kV, that appreciable oil quantities can be saved. An oil ratio, for instance, for average 132 kV full-oil to minimum-oil breakers is 3,000 to 300 gallons or 10 : 1 ; for lower voltages it was considered that drastic measures to cut oil capacity were not justified and this opinion has been shown to be substantially correct in view of the low rating of oil fire danger to-day. Reliable and fully tested circuit-breakers are a much better safeguard against fire than minimised oil ; that is if oil is to be used at all.

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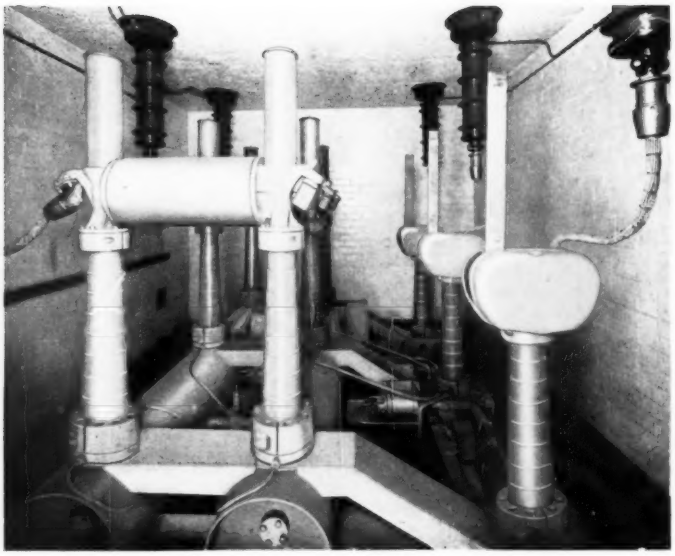


Fig. 8.—Interior of a circuit breaker house referred to in Fig. 7.

Air Circuit-Breakers.

As previously mentioned, air-break breakers are available for low-voltage installations, and at 3,300 volts, and will be manufactured up to 11,000 volts at least as soon as designs can be made to compete with modern oil circuit-breaker units at this voltage. Air-blast breakers are available for most British standard ratings and voltages from 3,300 volts and have been developed for outdoor use for 33 kV and above. Noise and exhaust blast difficulties have now been solved and except where these are tolerated to save space, modern units do not suffer from either of these disadvantages and, coupled with this advance, air consumption is being progressively reduced. Initial difficulties with leaks at valves and pipe connections have been overcome and methods of reducing the humidity of the air before feeding it to the breakers have proved entirely satisfactory.

Completely new technique will be required before a faster practical interruptor than an efficient air-blast breaker interrupting chamber is developed, as with the interrupting effort supplied to the arc, it is extinguished at the first possible practical moment, i.e., the first current zero or, if not the first, the first reasonable zero, depending on the point in the current wave at which the contacts separate. Further reduction of total break time can only come from speeding up the auxiliary equipment which is largely a function of economics. High-speed mechanical equipment requires precision in manufacture.

The air-blast circuit-breaker because of its mechanical flexibility, lends itself very easily to high-speed auto-reclosing with or without phase discrimination, that is to say, all three phases may be opened and reclosed at once or any one may be selected while the other two remain closed.

Complete units of the metal clad type built up of air filled chambers containing busbars, connections, etc., either under air pressure or fed with conditioned air and incorporating air-blast circuit-breakers, are being developed for indoor and outdoor use.

On air-blast circuit-breakers not employing resistance switching, voltage control units are fitted to prevent the possibility of high transient switching surges being produced, irrespective of the characteristics of the circuit to which the breaker is connected. When resistance switching is employed the resistance, which is cut into the circuit for the last half cycle of arcing, is calculated largely to damp out the natural oscillation caused by a change in the circuit, i.e., the operation of the breaker. On higher voltage, resistance switching is to be avoided if possible due to insulation problems, but by shunting the interruptor with a voltage controlling unit any over voltages produced are discharged harmlessly.

Oil or Air.

Within the scope of the air-break breaker for applications where fault capacity is high and/or operation arduous or frequent, there seems little difficulty in making a case in favour of the air-break unit. For other applications where fault capacity is low and operation not likely to be arduous and therefore maintenance not heavy, oil circuit-breakers should satisfactorily meet the case.

For the lower fault ratings up to 11 kV, air-blast breaker equipments cannot yet be made economically, but for higher ratings and voltages where economically the two types are more evenly placed, factors affecting choice may be summarised as follows :—

Maintenance (including cleanliness and ease of handling—in favour of air-blast.
Space—in favour usually of oil-break.
Speed of operation—in favour of air-blast.
Fire risk involving fire protection equipment—in favour usually of air-blast.

Foundations—in favour usually of air-blast.
Auxiliary requirements—in favour usually of oil-break.
Mechanical performance—in favour usually of air-blast.

Automatic Reclosing.

There are two distinct uses of circuit-breakers fitted with automatic reclosing features. The simple arrangement makes provision for a breaker to reclose automatically a number of times at suitable time intervals when feeding a spur overhead line supply at an unattended substation. This is used to minimise the protracted outage times to faults which do not clear themselves, and as a good average the ratio of non-permanent to permanent faults is ten to twelve to one on overhead lines.

High-speed automatic reclosing is applied to high-power interconnectors, usually overhead lines at extra high voltage between big power stations, and its primary object is to minimise the outage of the interconnector to a few cycles where possible, and thereby improve the stability of the system during fault disturbance. It can well be visualised how if one tie is cut for more than a few cycles, large parts of a system become overloaded and fall down like a pack of cards. In this connection there are on some power systems interconnectors which, once maintained open, are not easily reclosed unless load is considerably reduced to obtain synchronism. The success of auto-reclosing depends on the use of a breaker which will clear a fault in the minimum of time to avoid a large disturbance on the system caused by overload, then reclose in a time usually not less than 8 to 10 cycles suitable for the self-clearing of the fault. One reclosure is usually employed only, as if the first fails a second seldom succeeds. Systems have been operated successfully in America for a number of years, employing fast reclosing of interconnector lines and variations have been worked out, one of interest being used with double circuit lines which are busbarred on the low-voltage side of the transformers at each end. Each line is equipped with high-speed reclosing breakers at both ends on the H.V. side of the transformers, also at each end a high-speed breaker is connected to parallel the two high-voltage windings of the transformers. The arrangement is such that when either line breaker is open the tie breaker closes, although normally it is open when both line breakers are closed. This has been found to be a very effective way of reducing to a minimum the overall reactance of the interconnector when one line is cut momentarily or for a period, at the cost of only two extra breakers instead of four which would be required if the line were sectionalised at its mid-point. When the interconnector is too long this method is not satisfactory and the line has to be sectionalised at more than one place along its length so that when a fault occurs only a limited length of one of the circuits is lost, and the overall reactance is kept within suitable limits.

Some Examples of Applied Photography In Aero Engine Research.

by H. D. GOULDING, B.Sc., A.C.G.I.
Member of the Technical Staff of D. Napier & Son Ltd.

The application of photography has now come to be closely associated with a number of branches of engineering ; aero engine research is no exception. It should not, however, be assumed that the application is always straightforward. The behaviour of the photographic equipment may be well-known, and the full characteristics of the sensitized emulsions may be readily available, but when the camera and plate are brought together to aid a particular investigation it is usually found that a considerable amount of development work may be necessary before this particular application is a success.

Applied photography may, for convenience, be generally classified under the following headings :

1. Still Photography.
2. Cinematography.
3. Instrument recording.

These headings may further be sub-divided according to factors which are peculiar to a particular category.

In still photography the mode of illumination would be the defining factor, for example, continuous illumination will relate to record or illustrative photography while intermittent illumination would cover point source spark gap, gas discharge, and stroboscopic illumination. Each of these require a special technique but

common to each is the photographic plate from which is eventually produced an image of the illuminated object and a permanent record secured.

Cinematography on the other hand generally requires a continuous source of illumination, and therefore another form of differentiation must be made.

It is usual to subdivide this category according to the rate at which the frames are exposed in the camera. Low frame frequencies are associated with normal 16 or 24 frames per second, while at the other end of the frequency scale several thousand per second fall into the wide category of high-speed cinematography. Naturally such high speeds demand very specialised equipment.

Instrument photography which is usually associated with recording cathode-ray tubes and mirror galvanometers may employ either single-exposure cameras or continuous-film cameras. In the case of the single-shot instrument the exposure must be such that it will embrace a complete cycle and the spot brightness must be sufficient to produce a satisfactory exposure at the required writing speed. The continuous film camera carries a loop of film on a drum or a steady supply of film from a magazine. In each of these cases the motion of the film constitutes the time base and this must be such that it will resolve the necessary detail in the wave formations.

Examples of each subdivision will be discussed giving one application associating it with a research problem of Napier aero engines.

In each case the subject will be treated sufficiently fully to cover design, manipulation of the equipment, and to some extent the subsequent interpretation of typical observations.

In this generalised treatment a certain amount of detail will have to be taken for granted as it is hard to justify space that would be required to cover points of only specialised interest. However, care will be exercised not to dwell on purely spectacular aspects of photography and so tend to lose sight of its full capabilities. The examples treated are by no means exhaustive, and are intended to be records of work actually conducted which it is hoped will be of general interest and especially to those engaged upon similar investigations.

The Approach to an Investigation.

The importance of a careful approach cannot be over-stressed. Much time and effort can be saved if the full details and requirements of a test are considered in relation to available photographic equipment. It is also essential to become fully acquainted with the nature of the entire investigation if the required subject matter is to be interpreted correctly photographically.

More often than not it is the governing factors of the test which suggest the ideal photographic technique, provided the latter satisfies such questions as—what exactly is to be photographed ; how is it desired to photograph the subject ; and is the appropriate equipment available ? The answer to the last question is usually in he negative and in view of the high cost of this equipment it is found that modifications to existing apparatus in one form or another will have to be adopted. The success of the adaption will be to some extent dependent upon careful planning.

To indicate how circumstances govern procedure, consider two problems in general detail.

It is required to record photographically the entire operation of a non-cyclic high-speed linkage mechanism. Firstly, experience has shown that linear velocities of this type of equipment usually fall within the scope of high-speed cinematography, and if the optical components will resolve the necessary detail the high-speed camera would prove the most direct approach.

If on the other hand, for example, researches into fuel spray formations call for records of finely divided particles of fluid, travelling at high velocities in the vicinity of an injector nozzle, a totally different technique will be required.

Velocities are much higher than those associated with the linkage mechanism and the particles are very much smaller, in most cases only a few thousandths of an inch in diameter, so shadowgraph diffraction photography would have to be employed using point source illumination capable of giving flashes of very short duration.

The details of such techniques will be discussed later.

Still Photography.

Direct Scientific Applications.

An example in the first category is an investigation into the characteristics of plain journal bearings. It was necessary to determine the effect upon the performance of bearings when variations were made to diametrical clearances, oil flows, end float clearances, the position of oil holes, the shape and position of oil grooves, and whether or not they were desirable. At the time of this investigation engine duties were being increased, and so, therefore, were the loads that these bearings were expected to carry. In an effort to increase the load carrying capacity of the bearings it was proposed to investigate the controlling factors and the characteristics of the bearings under various conditions of test. As the work proceeded it became increasingly difficult to interpret the whole problem in definite quantitative terms, and it was therefore necessary to explore other methods of observation to supplement those already being made. Visual methods were explored.

A transparent bearing 1½ in. dia. and 1½ in

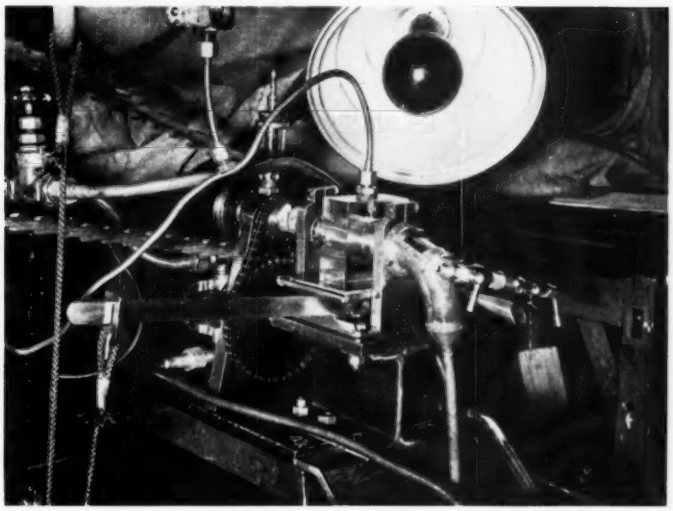


Fig. 1.—An experimental rig to investigate the behaviour of oil films within a transparent bearing. The lamp emits ultra violet radiations which fluoresce the oil film.

wide was prepared from a laminated Perspex block, the plastic being highly polished after machining to facilitate observation of the actual bearing surface. This bearing was mounted on a specially supported test journal and a load was applied through a pressure pad and lever mechanism while reaction was carried on the supporting ball-bearings of the shaft which were housed in vertical members of the rig frame to ensure correct alignment. This rig was provided with means of determining the oil feed and the approximate degree of aeration of the oil after it had passed through the bearing.

The oil pressure film when subjected to high loads and journal speeds of 1,000 to 4,000 r.p.m. was found to be very thin and difficult to observe under daylight conditions and shop lighting, so to increase the contrast between the oil film and the bearing surfaces a colloidal graphite stream was injected, this polluted the film and gave an idea of its extent and shape. This method was found to be very dirty and unsatisfactory and was quickly superseded by employing near ultra-violet radiations to fluoresce the oil film. A high-pressure mercury arc in a quartz envelope surrounded by a special filter bulb was employed as a light source and this gave very good differentiation between the fluoresced film and the bearing surfaces, and the results were so encouraging that it was at once decided to record the series of tests photographically.

The general requirements were straightforward, employing the rig as shown in Fig. 1. In conducting a test the load and speed were adjusted, and conditions were allowed to stabilise, the arc lamp also having been switched on and allowed to achieve its maximum brilliance. The oil film was slightly unsteady at high speeds, therefore it was necessary to use the fastest possible exposure permitted by the intensity of illumination and it was found that reasonable negatives were obtained with an exposure of 1/10th second at a lens aperture of f2.8. A typical example, Fig. 2, has been included to give a general impression of oil distribution around a plain feed hole when the bearing was loaded radially. There are two bearings with different clearances on the test journal in the illustration, and the change in the oil film will be apparent. The journal speed was 2,000 r.p.m.

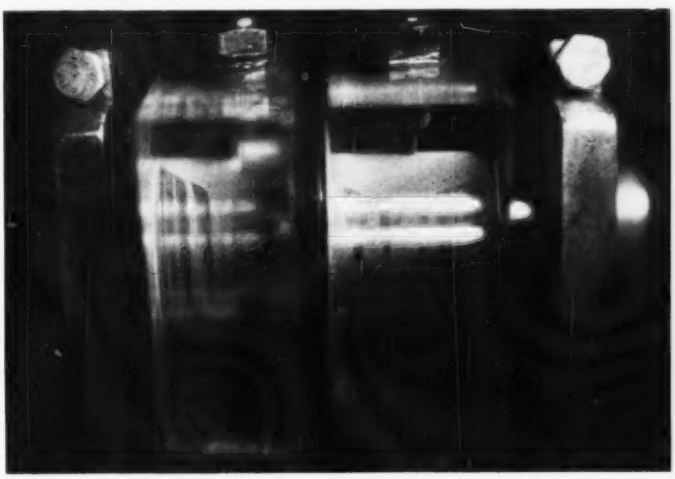


Fig. 2.—Two test bearings on common shaft. The effect of misalignment upon the oil film is apparent in the left-hand bearing.

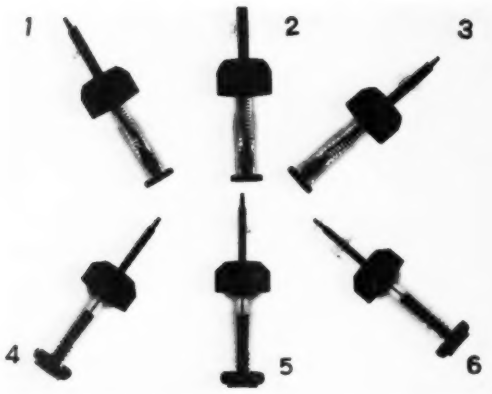


Fig. 3. X-ray photograph of several plugs. This enables imperfections to be detected.

Photomicrography.

Another application of direct scientific photography relates to the examination of fractures in sparking plugs. It was found that under high-duty conditions the plug tips were unable to withstand high combustion temperatures. The point and the main stem were made of platinum and silver respectively and welded together. This appeared to be the weakest part of the construction. A number of plugs were subjected to X-ray examination after being removed from the engine. See Fig. 3. This enabled the condition within the ceramic tube to be determined, and cases of fracture have been recorded near or at the weld. Fig. 4 shows an enlarged view of this type of failure. The investigation was extended to a metallurgical examination of a polished section

Fig. 4.—Photograph of a fractured spark plug tip.

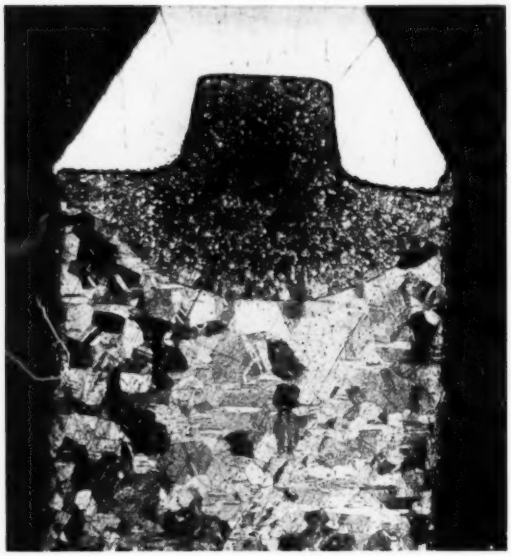


Fig. 5. Photomicrograph of the plug tip showing crystalline structure. Note differentiation between metals, in particular the spigot bond of tip to stem.

through the tip and weld : Fig. 5 is a representative photomicrograph, and was obtained from a projection microscope whose magnification was approximately 200 diameters. The definition of the chemically-etched metallic structure is good and gives clear differentiation between the silver stem, the silver weld, and the spigotted platinum tip. This form of junction between stem and tip gave satisfactory results.

Although the greater part of this investigation may have been done visually the value of an accurate photographic record could not be questioned, as it enabled the whole development complete with its successes and failures, to be readily available for reference. There are also other technical advantages in recording observations photographically since the use of optical filters and plates with different spectral sensitivities give a large degree of control over the whole process. This enables emphasis to be put on the part of the metallic structure which is of particular interest. It enables the differentiation to be obtained that may be essential to reveal this structure, that might otherwise pass unnoticed by visual observation.

A further example of a metallic structure is shown in Fig. 6, which illustrates a section through a research lubrication jet. Jets of this type were at one time being considered for use on spray lubrication, for the main nose-piece gear-reduction system of the Sabre engine.

The complete jet was produced from a solid

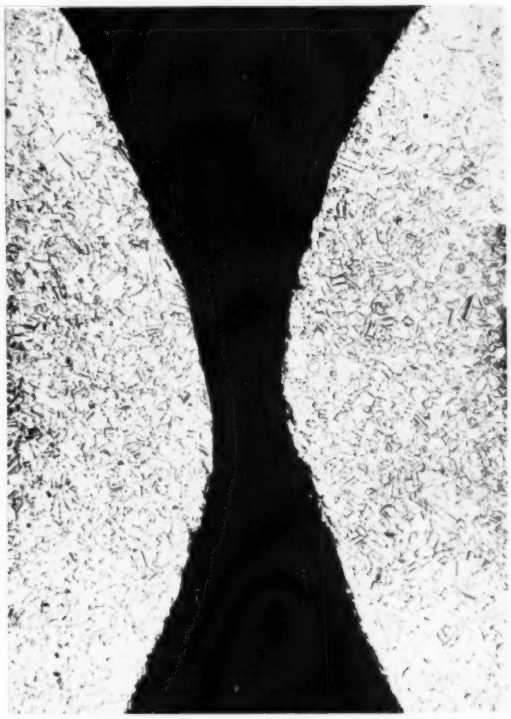


Fig. 6.—Microphotograph of cold rolled oil jet to examine orifice section and cold working effect on the metallic structure.

piece of aluminium which was previously drilled and then rolled into shape. Later it was placed in a bending jig which formed lips and produced a slit orifice to confine the resultant oil spray to the form of a bat's wing. This was designed to cover the width of the gears in question.

The method of production was suggested as a possible alternative to the usual practice of drilling a large number of small holes in a cast blank. During the course of this investigation a considerable amount of experimental data was obtained on the performance of these rolled jets, and it could generally be regarded as encouraging.

In order to examine the effect of cold working and rolling upon the metallic structure a number of sections were made of the jets in various stages of production, which also enabled the consistency of the throat diameter to be determined.

The records obtained for analysis were magnified approximately 25 times.

Record Photography.

An important application of still photography is to record special phases of a particular process of a mechanical operation, and to illustrate the relationship of one piece of equipment to the whole installation. Photographs of this nature are of great value both from a scientific point of view and for illustrating reports and other technical matter. Often it has been felt that more use could have been made of the camera to illustrate a particular detail, although a good print can never replace a good description it may well be said that a photograph would clarify a number of detailed points which would otherwise remain obscure. As an example of this nature, Fig. 7 has been included. It was required to braze together two concentric cylinders, the inner member having a ribbed surface. The cylinders were cleaned mechanically and brazing wire was threaded into machined grooves on the faces of the ribs, the outer cylinder was pressed on and the entire assembly, placed in a muffle furnace, and raised to the required temperature. In the light of experience it was found that the nature of the joint and its shape called for varying quantities of brazing metal, and to achieve this, standard wire was bent up in a series of compressed loops. This was laborious to perform by hand and it was decided to achieve similar results by a machine, a view of which is shown in Fig. 7 It will be seen how the 10 wires may be bent in a single operation by the motion of the oblique jaw and guide, the jaw gives a definite angular set to the series of wires passing through the machine, which are looped up by the subsequent

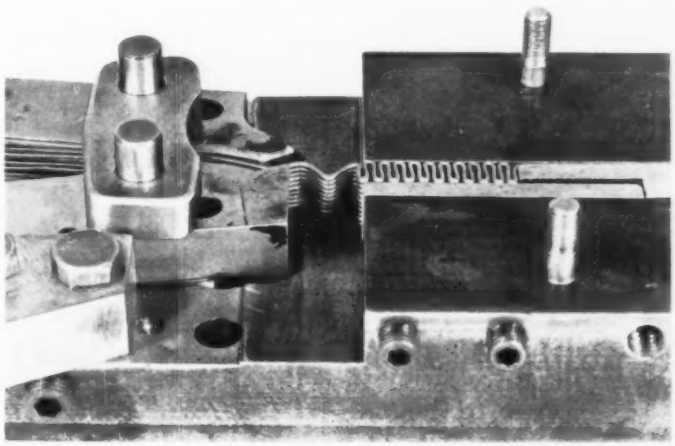


Fig. 7.—Process illustration of a particular mechanism to crimp brazing wire.

Fig. 8.— Record photography showing precise position of main bearing thermo-couples in a "Sabre" engine crankcase.

movement of the jaw in a forward direction. The loops as they are developed are confined in limit stops as shown in the illustration. This enables an increased mass of brazing material to be accumulated at the particular part of the joint and so to act as a reservoir as the molten metal is carried away by capillary action. The inclusion of the illustration enables the general operation in bending the wires to be more readily appreciated.

A final example of illustrative photography is the all important aspect of illustrating technical reports. This enables the reader to form a very accurate impression of the entire subject no matter how complicated. If, for example, a report is to be issued on temperature measurements of main engine bearings, where the exact position of thermo-couples is important then even if dimensioned drawings are included, a photograph similar to Fig. 8 will convey a good deal of important data, which may to some extent be already covered by the text, but nevertheless, it will help to clarify the impression made on a reader who is unfamiliar with the precise details of the investigation.

Flash Photography.

Photography employing high-intensity flashes of short duration has a particularly wide field of application. The examples relate to the development of a centrifugal atomiser or spinner, which is closely related to the engine supercharger and fuel injection system. The spinner is responsible for breaking up the fuel into a very finely divided spray. The fuel is fed into the centre, or eye, of the spinner from a jet approximately $\frac{1}{4}$ in. dia. and is thrown out over the surface in a thin film by centrifugal force. This thin fuel film leaves the sharp edge of the spinner and forms a series of droplets, resulting in the required spray whose droplets are thrown off into space with an initial velocity approaching that of the periphery of the spinner. In order to secure a good performance from an internal combustion engine the fuel and air must be supplied in the correct quantity and the two must bear a definite ratio to one another, and must also be supplied in such a form that it is made readily available to the rapid combustion process.

It was decided that the whole atomisation process should be the subject of a detailed investigation. An experimental spinner 7 in. dia. (see Fig. 9) was mounted on an air turbine motor capable of speeds up to 6,000 r.p.m., the whole erected on a angle-iron frame-work, diagrammatrically illustrated in Fig. 10. The spinner took the form of a saucer-shaped disc whose maximum peripheral speed approximated to that of the actual engine spinner. The object of this investigation was to obtain design data for spinner sprays, also their reaction to certain engine variables.

During the course of the investigation particular attention was paid to the spinner speed, fluid injection velocity and flow rates, also the surface condition and detailed shape of the actual spinner.

This type of work clearly indicated the use of

Fig. 9.— Experimental Spinner

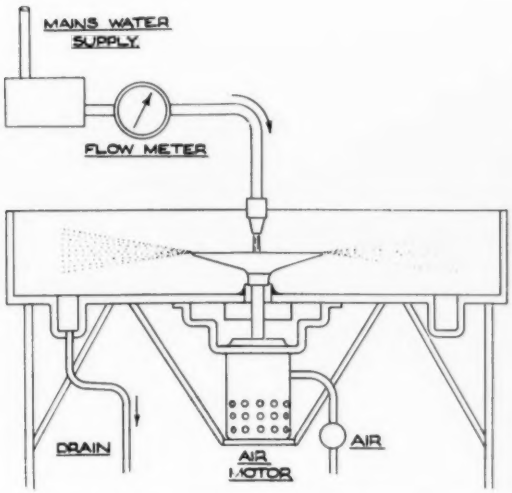


Fig. 10.—Rig to investigate the characteristics of a centrifugal spinner and its associated fuel spray.

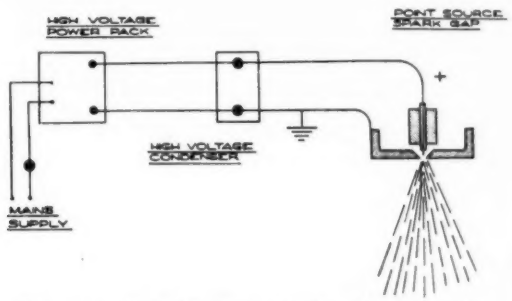


Fig. 11.—Schematic spark circuit showing section through point source spark gap.

diffraction shadowgraph photography, as explained later, for recording the high-velocity spray droplets; also single high-intensity flash illumination to photograph the surface conditions of the actual fluid flow, and wave formations over the surface of the spinner.

The first part of this investigation made use of the spark gap as the source of illumination.

Fig. 11 shows in diagrammatic form the essential features of the equipment. The power is supplied from the mains to a high-voltage transformer, which charges through a rectifier the 0.5 mfd. reservoir condenser to its peak value of 15 kV. The specially designed point source spark gap was connected in parallel with the condenser to form a discharge path. When the potential was such that the air gap became ionised, the energy stored up in the condenser discharged across the gap, giving rise to a flash of great intensity of several microseconds duration. The

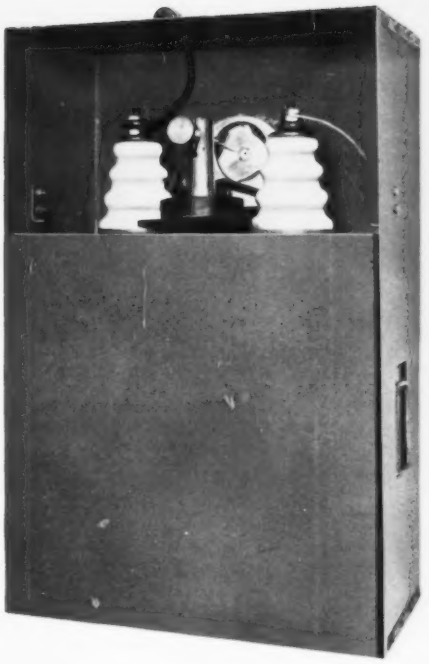


Fig. 12.—Rear view of discharge unit; the gap being supported direct on the reservoir condenser.

spectral composition readily affected suitable photographic plates. The spark gap was designed to have a relatively small aperture, the central positive electrode was insulated in a quartz tube to confine the discharge and to ensure it remained

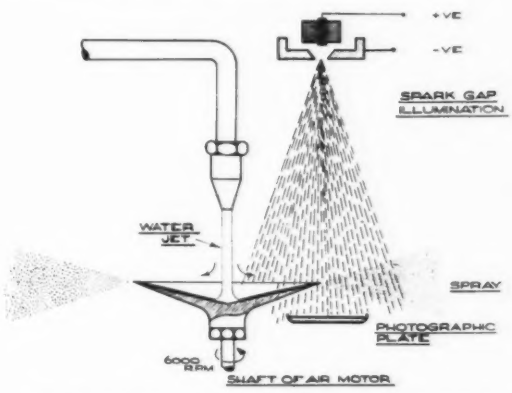


Fig. 13.—The point source spark gap in position on rig and showing the relative position of the photographic plate.

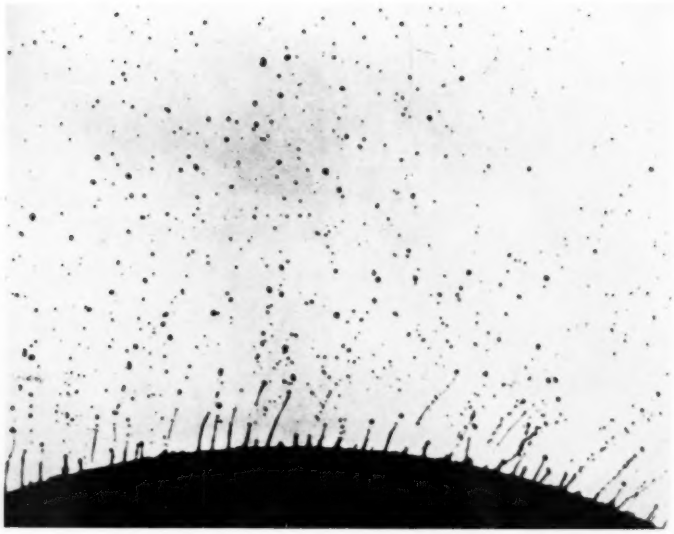


Fig. 14.—A typical shadowgraph of the spinner's edge showing formation of the droplets.

concentric with the actual aperture. Fig. 12 shows clearly the spark gap situated as near as possible to the condenser terminals. As the duration of this flash was determined by the circuit parameters, therefore, precautions were taken to reduce these to a minimum. The spark gap and condenser were mounted 5 ft. from the spinner and directly over the area to be photographed, the plate was situated as near to the spray as conditions permitted, and precautions were taken to ensure that the plate did not come into contact with stray droplets. The plate holder was supported about 6 in. below the edge of the spinner, see Fig. 13. Exposure was effected by darkening the room, drawing the slide, and the condenser discharged. The images found on the plate were shadowgraphs of the spinner edge showing the formation of the droplets as they left. In the case of the smaller particles they would cast what are termed diffraction images ; these are images produced by opaque particles where dimensions permit interference between two diametrically-opposed diffracted rays. This produces the black rings that are seen around a number of the fainter images. On account of this diffraction effect it is impossible to determine the dimensions of the particles by shadowgraph photography. This limitation did not affect the investigation as it was confined to spray distribution. If particles size had been required an optical system could be employed between the spray and the photographic plate. In other words, photomicrography would have to be employed with flash illumination, then sizes of the particles could be measured directly from the plate.

An example of shadowgraph photography employing the spark gap is shown in Fig. 14. The formation of the droplets can be clearly seen at the end of the fluid jets leaving the spinner, but in this particular case the speed and fluid flow rate were low, so as to obtain a clear example. When, however, the spinner is subjected to engine conditions the fuel leaves the edge in a thick mist composed of finely divided particles. A plate exposed under these conditions would give a record as seen in Fig. 15. This plate shows a large number of diffraction images, and the actual particles size was of the order of .002 inch. A large number of plates were exposed in different regions of the spray and a number of variations in spinner speed and fuel flows were investigated.

It was thought that the manner of flow over the surface of the spinner might influence the consistency of spray and perhaps also the

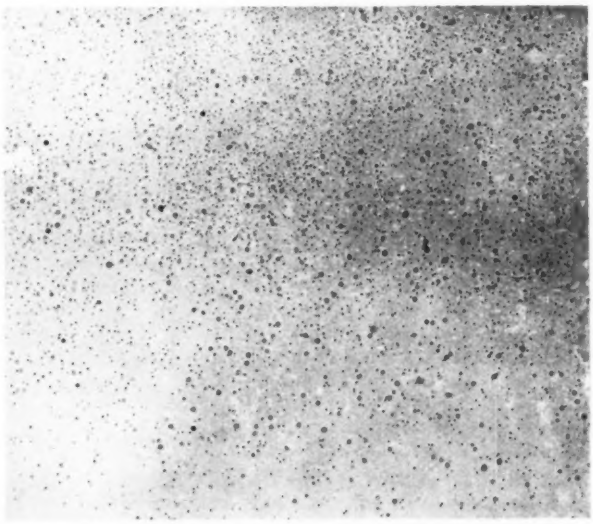


Fig. 15.—An enlarged shadowgraph of an atomised spray showing a number of droplet diffraction images.

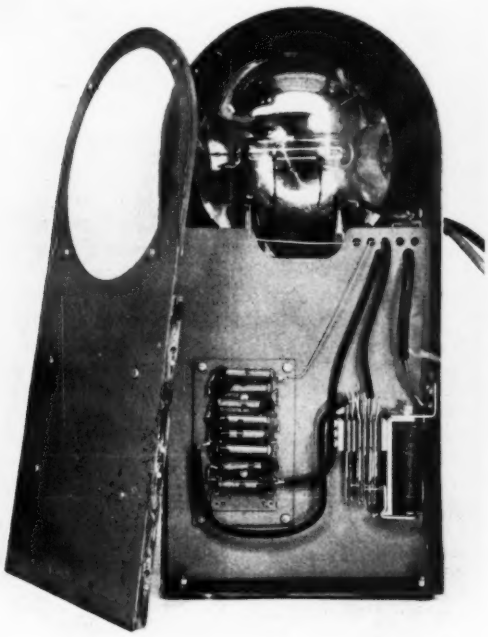


Fig. 16.—The Arditron gas-discharge lamp for general high-intensity flash illumination.

stability of the engine. In order to illuminate the whole spinner the Arditron discharge lamp illustrated in Fig. 16, was employed. This consists of a glass envelope containing the three electrodes, and is operated from a circuit similar to that described for the spark gap. On closing the relay switch a potential is applied to the ionising ring on Arditron lamp causing it to discharge the condenser, thus effecting the exposure.

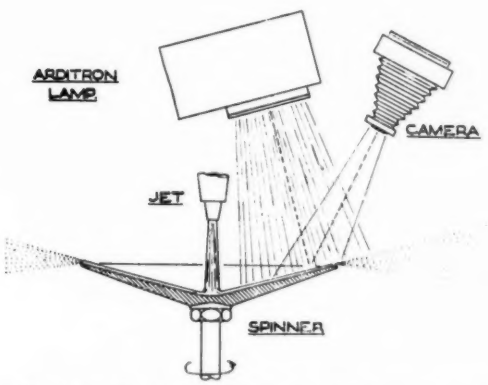


Fig. 17.—The Arditron lamp in position over rotating spinner to secure high definition surface photographs.

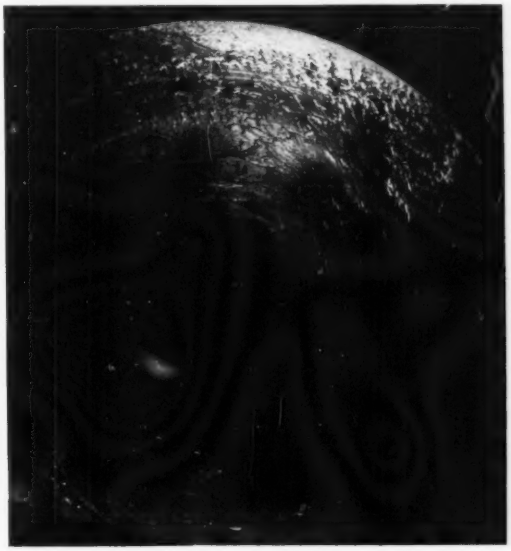


Fig. 18.—A typical surface photograph of the experimental spinner when atomising three gallons of fluid per minute.

The Arditron lamp is capable of very short duration flashes, approximately one microsecond. The intensity of flash is considerable and permits fully-exposed negatives to be obtained of relatively large subjects situated 20 ft. from the camera and in most cases it is only necessary to employ lenses of low aperture. The lamp was mounted in a steel case containing the condenser and electrical relay mechanism. The high-voltage switch enabled the operator to flash the lamp at any desired phase of the investigation. The two cables seen on the right-hand side of the case connect the lamp and condenser to the high-voltage power pack. A concave mirror of short focal length may be seen at the back of the case to reflect the light on the spinner. The actual procedure was very similar to that employed in the spark photography. The camera, which had been previously focussed on the spinner when stationary, was loaded with a plate. The conditions of the spinner were adjusted, and allowed to stabilise for some minutes before the exposure was made. The Arditron lamp was mounted above the subject in such a position that the beam was reflected by the spinner into the camera to obtain maximum illumination and the greatest differentiation between wave formations and the spinner surface. See Fig. 17.

A typical example of the spinner surface is shown in Fig. 18. The irregular concentric wave

formation will be apparent, and by examining a number of plates it was found that there was no consistency between a wide range of speed and fuel flows. It was thought that the actual surface of the spinner would have the greatest influence upon the fluid film but it was found experimentally that even between the wide extremes of a polished and a shot-blasted surface there was a little change in conditions. It was hoped to determine conditions that would produce a uniform film, because it was thought that it would greatly influence the production of a uniform spray.

The series of tests on the distribution of spray proved conclusively that the spinner speed was by far the most important variable which greatly influenced the saturation limit of the spinner. This was said to be saturated when it was unable to atomise the quantity of fuel supplied to it, and under these conditions sheets of solid fuel could be seen to fly off into space ; this unatomised fuel would be unsuitable from a combustion point of view. The initial flow velocity was found to influence the atomisation and the resultant spray. The distribution was relatively uniform as long as the fluid flow was below the saturation limit. The surface of the spinner, the degree of concavity, and shape of edge were found to be variables of the second order of importance. In the case of the Arditron flash photography a complete lack of consistency in the general wave formation was experienced and these results were contrary to the conception that the spray had been formed by a uniform and continuous film leaving the edge of the spinner.

Stroboscopic Photography.

In this technique it is the series of cyclic flashes which create the impression that the rotating or cyclic function is stationary. If a shaft has provision for a contact breaker it will enable the discharge lamp circuit to be operated at the point where the circuit is either opened or closed, thus producing the flash. If the position of contact is moved relative to a fixed point the phase displacement between this point and the flash will have altered by a similar angular movement, thus revealing in apparently stationary form, another part of the cycle corresponding to this new phase position.

If there is sufficient illumination it becomes a simple matter to record this photographically. The duration of exposure is a function of the intensity of illumination per flash and the repetition frequency of the cycle. In many cases, however, the lamp may flicker at higher speeds, and there will be variations in phase position from one flash to another. This will produce an apparent sudden movement of the "stationary" object. It is therefore highly desirable from a photographic point of view to reduce the exposure to a minimum, the camera shutter being adjusted to give an exposure whose duration embraces one flash for certain and possibly two. Under these conditions best definition will be obtained. In the early part of the war, use was made of simple neon lamp stroboscopes and good results were obtained on a plate camera with an exposure of one-fifth of a second and a lens aperture of f2.8. In recent years, however, there has been a marked increase of greatly superior equipment available. Many of the lamps include their own time bases which make it unnecessary to have a contact breaker ; although this or its equivalent, should always be included in the circuit if the phase position is to be consistent. The discharge lamp normally fitted to the complete hand equipment is of little use for photography, but provision is usually made to operate a special lamp which will provide adequate illumination. The spectral composition of the flash is highly suitable for certain blue-sensitive emulsions, and its duration may be as low as several microseconds. This type of apparatus has been employed to investigate the general characteristics of engine injection sprays, and to determine the nature of the flows, where a mechanical defect might have a considerable influence upon the nature of flow. The natural frequency of a bouncing spring in an injector

Fig. 19. *Stroboscopic illumination applied to fuel injection spray research.*

nozzle might have given rise to an intermittent spray, which was naturally undesirable. Two jets that were to be subjected to investigation were connected to an existing fuel injection system, and it is always important to employ conditions comparable to those of the engine as variations in pipe length between the injection pump and nozzle can influence the overall characteristics considerably.

The nozzles illustrated in Fig. 19 produced a conical spray of elliptical section and for this reason the two were mounted in such a way as to present to the camera the maximum and minimum dimensions of the spray cone. A contact breaker was secured to the shaft to enable an accurate phase relationship to be maintained between the injection and the flash. The degree scale can be seen in the background with the pointer moving over it ; by taking a number of pictures at different phase poisitions it is possible to determine the growth of the cone or its decay at the end of the injection period. A scale is included to enable the overall length variations to be obtained. A series of pictures were taken on a Leica camera with an exposure of $\frac{1}{25}$ of a second and at the full aperture f2. The flash relative to the injection period was varied to cover the complete cycle so the whole event could be recorded photographically. By comparing a series of prints it was possible to obtain the relationship between the spray development and phase position.

By slight variations in technique this method may well be applied to other cyclic phenomena. Although photographically it may be closely related to single-flash photography there remains the very important difference that the eye through the persistance of vision is able to construct a complete picture. This has its advantages in connection with a number of similar investigations.

Photo-elasticity.

The modern developments in the photo-elastic technique make any treatment of applied photography incomplete without reference to the subject of optical stress analysis.

In recent years there has been an increasing amount of attention paid to photo-elasticity, and a number of articles in the technical press will have acquainted its readers with the potentialities and basic principles of the subject. These strides in optical stress analysis may be mainly attributed to the modern development of plastics and the materials employed to-day are considerably more suitable than those used in the early work of Professors Coker and Filon. In order that a plastic may be employed for this technique it must satisfy several requirements, the most important of these is optical sensitivity, this governs the number of fringes that will pass through any given point when the model is subjected to load. The ease with which a plastic may be machined is important from a production point of view, generally speaking small models can best be prepared by profiling with a sharp saw and filing to the required dimensions. Great care must always be taken in all these operations to ensure that excessive heat is not generated close to a finished boundary, if it should, signs of permanent internal stress are likely to appear in the finished specimen. Furthermore, the interval of time between model production and its use in the polariscope should be as short as possible as this has the effect of reducing time edge effect to a minimum. Transparent Bakelite is one of the most suitable plastics but it is not available in sufficient quantities. Catalin, which is obtainable in this country, has proved to be very satisfactory and has been used throughout the Napier series of investigations.

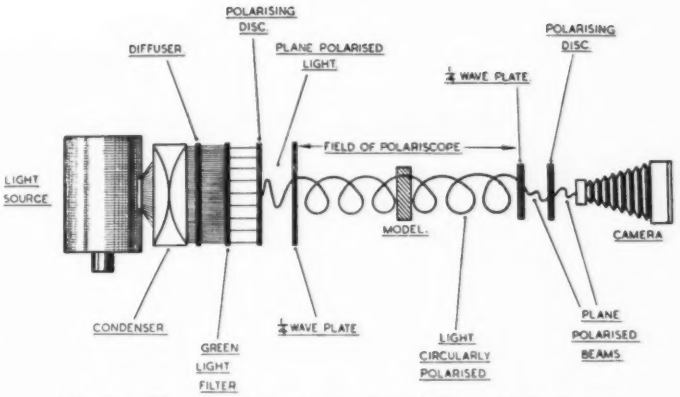


Fig. 20.—The essential components of a circular field photo-elastic polariscope.

Suitable plastics make it no longer necessary to measure small changes in the optical effect produced by the application of a load. Their high sensitivity enables this effect to be determined directly by counting the number of complete fringes that have passed a particular point in the model during the application of load. It will be appreciated that if calibration test pieces are prepared it becomes a simple matter to determine the relationship between these black fringes and the applied load in terms of principle stress. This has another significance in that the

actual retardation or fringe value may be obtained easily by analysis of a photographic plate of the stress pattern.

An important advancement in recent years is the almost exclusive use of monochromatic light to obtain observations and photographs of the stress pattern. The illumination is supplied from a high-pressure mercury arc lamp in the protective housing of the polariscope, see Fig. 20. In the mercury specturm will be found a bright green band, and it is a simple matter to isolate this with a suitable optical filter thus producing monochromatic light.

This is valuable photographically as it enables plates to be selected which have the greatest sensitivity in the region of the wavelength of light employed, although to obtain certain observations it is still essential to use white light.

When a stress diagram has been photographed it is necessary to obtain the isoclinics, enabling the inclination of the principle stress planes to be determined, and later by graphical construction, the principle stress trajectories. Isoclinics may be seen and photographed in monochromatic light, but definition may be greatly improved if the filters are removed from the plane polariscope.

The circular polariscope, as employed for these investigations is of conventional design, the various components being indicated in the illustration, Fig. 20.

The camera employed on the polariscope was specially constructed in the laboratory, and consists of plate holders, a light-tight box and a portrait lens of 12 in. focal length with a maximum aperture of f3.5. Large plates were found to be superior to smaller negatives, which called for subsequent enlargement, which was a lengthy process and did not give results comparable with a contact print from the larger negative. Generally it was found that panchromatic emulsions were best suited to the mercury green line, and fast plates had to be employed even when using the 500-watt arc lamp. The loss of light was due to the high degree of absorption in the filters and optical plates.

Good negatives were obtained with an exposure of several seconds, although it was difficult to get the desired contrast between the black and white lines from a straightforward print.

It was an advantage to over-expose the plate and to treat it fully in a process developer. This produced a very dense negative for printing, but was treated by chemical subtractive reduction in Farmers' Solution ; a few seconds treatment produced a very satisfactory contrast between the background and the interference bands. A typical print from a negative produced in this way is shown in Fig. 21. This plate was taken from a series of exposures made during an investigation to determine the concentration factors at the roots of gear teeth.

Fig. 21.—A typical maximum shear stress diagram. The plastic gear tooth model being subjected to point load.

It must be appreciated that the stress diagram shown in the illustration relates to maximum principle shear and cannot be directly related to pure tension and compression, but to obtain these quantities the stress diagrams complete with a set of isoclinics, would be the subject of an involved analysis. The stress diagram may be of great value, but it would convey an incorrect impression if it were regarded as complete in itself. This point certainly calls for emphasis because of the general belief that such a diagram can be the end of insuperable difficulties—it is usually only the beginning. If, however, the subject is approached with caution and in association with other treatments of a particular problem, valuable qualitative and quantitative information may be obtained.

Cinemotography.

Normal Frame Speeds.

A Sabre engine was installed in a cold room in order to investigate the influence of low temperatures upon starting characteristics. It was

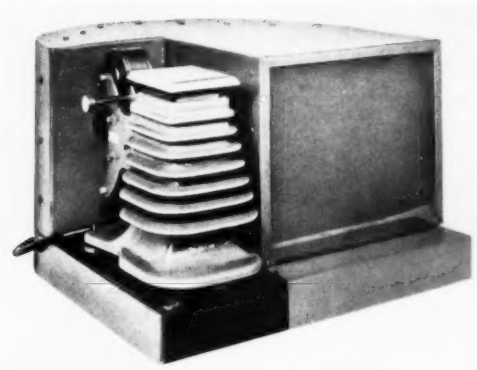


Fig. 22.—Reflex projector constructed to facilitate the analysis of 16 mm. films.

necessary to determine the relationship between torque, speed, and time; the first two quantities were translated into electrical signals which could be indicated on calibrated instrument movements; the time was measured by a large diameter stop clock. These instruments had specially prepared scales with which to facilitate good definition and were mounted on a panel near the electrical control gear and surrounded by reflectors. Sufficient illumination was provided to give adequate exposure and care was taken to ensure that the lamps were all placed outside a cone that would be the limiting position for glare and reflection. The 16 mm. cine-camera, which was a standard commercial instrument, was erected on a special iron stand, positioned so that the panel completely filled the frame. The camera speed was set at 8 frames per second, the correct aperture was determined experimentally to give optimum exposure and resolution. The duration of a complete test ranged from a few seconds up to a minute depending upon operating conditions. At the commencement of the test the film was set in motion, the cranking motor then turned the engine, indicating torque and speed on the instrument panel. As the initial frictional torques were overcome more power was supplied to the motor thus increasing the rate of turning, all this was performed automatically and the actual rate of speed increase could be controlled. On the conclusion of the test the camera was immediately removed to the dark room where the exposed portion of the film was developed and as such tests become a routine procedure a large amount of film requiring analysis was accumulated. The early procedure was to project the film at regular frame intervals on a screen, and to record visually the readings on various dials, but this operation called for a darkened room and was found to be inconvenient so attempts were made to use back projection. Tests showed this method to be successful, and it was decided to establish this principle in a more permanent form.

An instrument, shown in Fig. 22, was evolved for the purpose. It consists of a standard commercial 35 mm. projector modified to take 16 mm. film, mounted on a base which in turn supports a mirror system which reflects the plane of the projected image through 180° and casts it onto the ground-glass screen on the right of the projector. The whole is covered by a light metal box. The arrangement has proved itself to be satisfactory and permits the operator to control the film with the left hand while noting observations with the other. The "reflex projector" greatly reduced the time required to analyse a test, and the method of projection enabled the work to be conducted in ordinary laboratory lighting thus reducing the eye strain that was associated with earlier methods.

The data obtained from the cold starting tests was plotted, and curves drawn to illustrate the

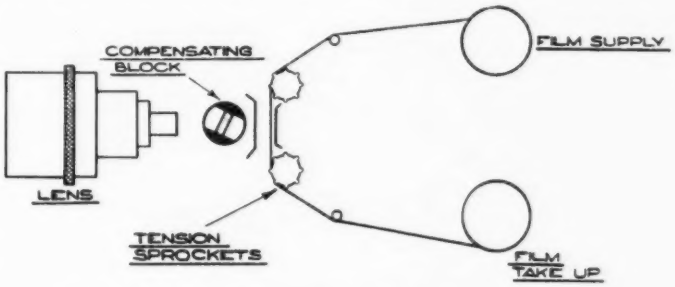
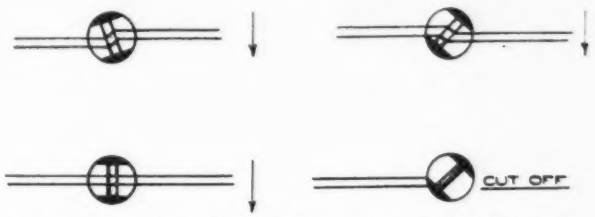


Fig. 23. (a) The mechanically interlocked transport mechanism on the Eastman Kodak high-speed camera.



(b) The optical rotating block to compensate for the film motion during exposure.

Fig. 24.—A typical investigation "set up" of the high speed camera. The side cover has been removed to expose the camera's mechanism.

breakaway characteristics of the engine under varying conditions.

This method of recording was a little laborious, but it enabled results to be obtained immediately without having to use specialised recording gear. This photographic technique has been found to be a valuable exploratory form of instrumentation to determine whether or not further complications are justified.

The High Frame Speeds.

The Eastman Kodak high-speed camera has been used on a number of specialised investigations in connection with engine and engine component development work. This camera has enabled observations to be made of many high-speed phenomena. The engagement of clutches, the action of jet lubrication on meshing gear teeth, the flow of coolant fluids through pipe bends and the behaviour of oil pumps under varying conditions. It will be appreciated that work of this nature calls for very high film speeds, and it was to meet such requirements that the Kodak camera was designed to cater for frame frequencies up to 3,000 per second. The camera differs from a normal-speed instrument in several ways. The film moves through the gate continuously, as distinct from the usual intermittent motion and this necessitates a specially designed optical system that will cause the image formed by the lens to travel down with the film during the period of exposure so as to ensure perfect registration. The essential details of the optical system are shown in Fig. 23 ; attention is drawn to the rotating optical compensating block. This consists of a rectangular block of glass with two optically worked and parallel faces.

The block is approximately .25 in. thick and is mounted in a drum which constitutes a barrel shutter, which is allowed to rotate in a very precise ball-bearing support and is mechanically coupled to the film transport mechanism ; the compensator is situated between the lens and the film gate. This means that special lenses must always be used on the high-speed camera, and these have been designed to have a large back working distance. The mechanically-coupled compensator will rotate as the film is drawn through the gate, in such a manner that it will cause the image to be refracted in an upwards or downwards direction depending upon the inclination of the block. This deflection is in sympathy with the film motion and the mechanism has been designed to enable the image and the film to travel together during the period of exposure. The whole mechanism is dynamically balanced on account of the very high speeds in the camera, the maximum linear velocity of the film is approximately 70 ft. per second. The camera has several features of interest, the automatic power cut-off switch, and the external sychronisation micro-switch.

The power switch is in series with the mains supply to the motor and is driven by the camera mechanism. The knurled setting wheel enables the operator to set the switch to cut-off at the end of 50 or 100 ft. of film through the gate to prevent racing when the camera is unloaded, this precautionary device has been found to be extremely accurate in operation. The synchronising switch operates in a very similar manner and is directly geared to the film motion, the dial is graduated in feet and enables the micro-switch to be set to open or close a pair of contacts at some predetermined position of the film. Thus an experiment may be automatically controlled by the camera. A general view of the high-speed camera is illustrated in Fig. 24. The internal mechanism can clearly be seen, the focussing tube that is extended through the back of the instrument will be noted. In this illustration the camera is shown attached to the tuning fork

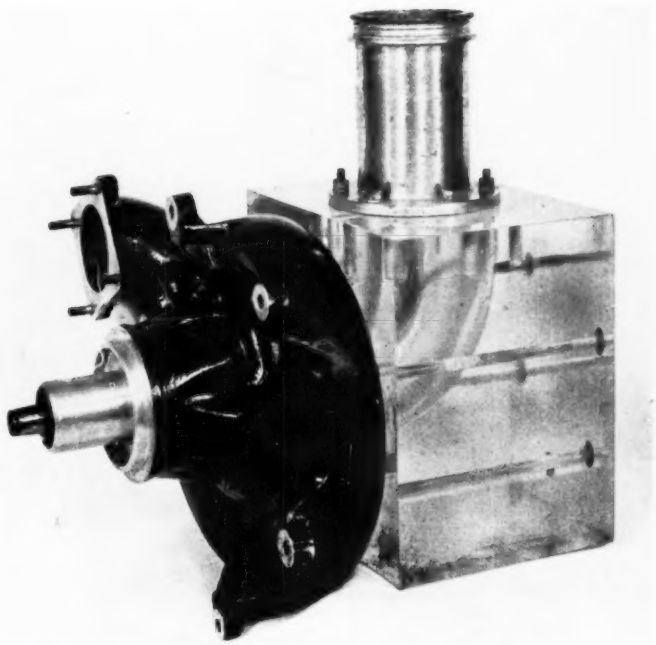


Fig. 25.—An experimental centrifugal water pump with transparent housing to permit cavitations at the impeller to be photographed.

operated time base, which intersects a light beam, and so makes a number of marks on the edge of the film, the space between marks corresponding to a definite interval of time. In the photograph the camera and time base are mounted on a tripod and are shown in the position for taking a shot of a spring mechanism and fuel injection pump.

In most cases the subjects require a certain amount of preparation, and the two pumps shown in Figs. 25 and 26 called for transparent bodies to permit observation of impeller and gears. Perspex has again played an important part, as will be seen from the illustrations. The blocks were fabricated from a number of sheets of Perspex under pressure, and their laminations although apparent under certain conditions of illumination did not interfere with the final photographic result.

The photographic aspect of the oil gear pump investigation may be regarded as a typical example of applied high-speed photography. The volumetric efficiency of a gear pump may be greatly influenced by the condition of the oil supplied to the pump. Scavenge pumps as fitted in the sump of an aero engine were called upon to handle quantities of hot oil containing a great deal of air in solution and suspension and the presence of this air had a very detrimental effect upon oil flows. Efforts were made to reduce the degree of aeration to a minimum by fitting a special separator to the suction side of the pump, but even this gave room for improvement.

A series of tests was conducted to determine methods of removing the air in the pump, or to reduce its detrimental effect to a minimum. It became necessary to observe the way the air behaved in the pump, and to study the disposition of the suspended air between the teeth as the pump was in operation. A standard pump was prepared from a plastic block having plane external faces, but with internal dimensions similar to those on the actual engine pump. The internal components, gears, shafts and bushes, and machining clearances were all standard. The experimental pump was mounted on a universal rig allowing the whole speed

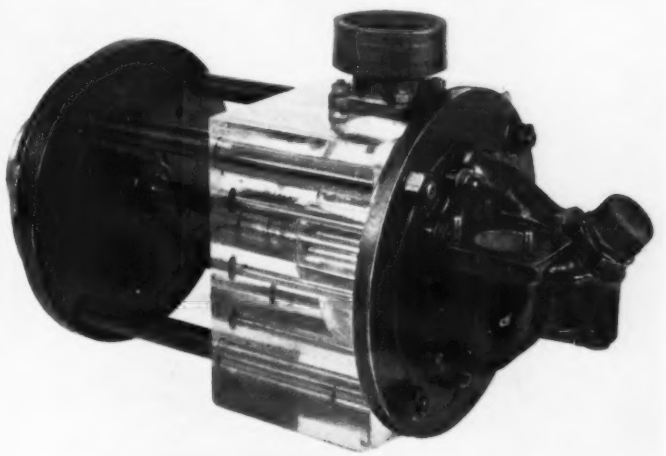


Fig. 26.—A Sabre gear-type oil pump to study the behaviour of aerated oil while passing from the low-pressure to the high-pressure delivery.

range to be covered. As the plastic did not permit high temperatures to be used it was necessary to use thin oil to give the equivalent viscosity of standard engine oil at the higher temperatures. Means of measuring oil flows, and the introduction of air into the lubrication system were incorporated in the rig.

A view of the pump including the gear teeth and the inlet and outlet ports was selected. As high camera speeds were required, several high-intensity flood lights were arranged to illuminate the subject matter. The camera was only a few feet away and the internal portion of the pump conveniently filled the frame. A number of high-speed films was taken of the pump when operating over a wide range of conditions. As the subjects were rotating continuously it was possible to project back on to a screen at 16 frames per second. This had the effect of reducing the pump speed from 3,000 r.p.m. to approximately 30 r.p.m. The analysis of these films indicated that the effect of centrifugal force upon the air bells in the oil could be neglected, and there was apparently no consistency in the way the incoming air bells were chopped and carried from the low-pressure side to the high-pressure outlet. This method of observation enabled the effect upon internal pump characteristics to be observed directly and also permitted the influence of design modifications to be appreciated visually. It is not suggested that the photographic method should replace any established test principle but it is very valuable and it can be employed together with other methods as a parallel investigation.

Instrument Recording—An Application of the Drum Camera.

A series of tests was conducted on a full-scale "Sabre" aero engine in an attempt to investigate the influence of firing order, port and induction manifold design on scavenging and engine performance. The Sabre was motored by a variable speed 700 H.P. electric motor directly coupled to the airscrew shaft. Thus it was possible to obtain the necessary speed range corresponding to the required engine conditions, with the exception that no fuel was introduced into the boost air. Fuel was not necessary for this particular investigation and it would have only constituted a severe fire risk.

Each manifold supplied the combustion air to one bank of six cylinders, and as each intake port opened according to a particular firing order, a charge of air was admitted to the cylinder. This loss of air to the system gave rise to a local reduction of pressure. When the port was closed the deficiency was made good by the forward rush of boost air, giving rise to a ram effect in the manifold air column which enhanced the supply pressure at the point in question. By altering manifold design it was hoped to tune the system, thus enabling the opening of the intake port to coincide with the peak of the pressure cycle at that particular point within the manifold, and so improve the scavenge efficiency.

In order to investigate the governing factors a complete cylinder block with the air intake manifold was subjected to a series of tests. It was hoped to determine the natural frequency of each part of the system, and the modulating effect produced by a complex system of reflected waves.

The experimental approach is diagrammatically illustrated in Fig. 27. A pendulum switch was released at a predetermined time and closed one set of segment contacts which were in circuit with a high-voltage relay, so discharging the reservoir condenser through a spark gap and emitting a shock wave.

The disturbance travelled up and down the manifold and the resultant wave at some particular point produced a signal in an electromagnetic pick-up. This was amplified and passed on to the horizontal deflection plates of a cathode-ray tube causing the spot to move in sympathy with the pressure fluctuations within the manifold. The movement was recorded on a simply constructed drum camera consisting of an 8 in. diameter aluminium drum accommodating a length of 35 mm. recording film and belt driven at 1,800 r.p.m. by a constant-speed electric motor. The image of the cathode-ray tube spot was formed by a short focal length lens of high aperature mounted in front of a manually-controlled shutter which was opened before the commencement of

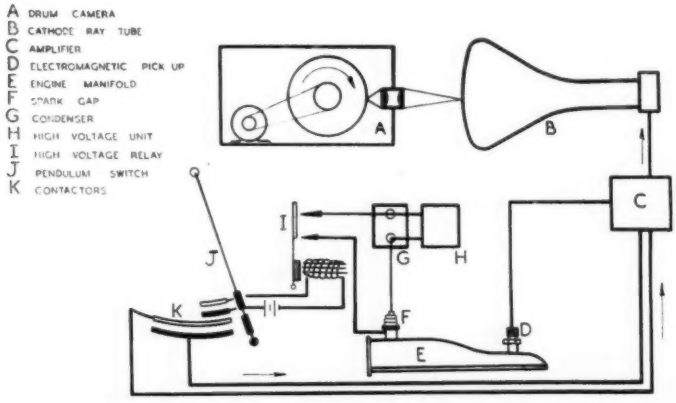


Fig. 27.—Drum camera applied to engine manifold investigations.

test, the drum camera and cathode ray tube being contained in a light-tight box. In order to ensure that the resultant exposure did not exceed one revolution of the drum the cathode-ray tube beam was controlled by another set of contact segments on the pendulum switch. The length of the pendulum governed the time interval between switching the beam on and off. The beam contacts were phased in relation to the high-voltage relay segments in such a manner that the beam circuit was closed before the spark impulse was emitted. The precise positioning of contacts and the length of pendulum were determined by experiment, and in spite of the very elementary method of the switch construction a high degree of control was maintained over a series of tests.

The relative positions of the spark gap and pick-up were altered after each test and a set of representative photographs of resulting waves obtained. A typical example is shown in Fig. 28.

As the film speed is known the frequency of the fundamental and modulating harmonics could be readily determined. A sharp vertical pulse before commencement of signal indicates the time at which the sound wave is emitted in relation to the trace, and its growth and decay together with the induced interference can be followed. This information was eventually correlated with data obtained from dynamic test and eventually led to a number of conclusions relating to manifold design.

Continuous Film Recording.

The previous example was suited to the drum camera as the high film speed enabled the sound waves to be resolved, and as the whole cycle of events was completed in so short a time it was possible to record it in a single revolution of the drum.

In the case of the following clutch investigation the duration of the function was much greater, but as a high degree of resolution was not required, the use of continuous film recording was clearly indicated.

It was required to investigate the characteristics of a particular clutch incorporated in a two-speed gear-box, whose output shaft was connected to an inertia mass capable of rotating up to 20,000 r.p.m. The whole system was driven by a variable-speed electric motor. The object of the investigation was to record the relative slip between the clutch and the cones during the engagement period from one speed to another. Experimentally this was not difficult. See Fig. 29.

Close to the inertia mass was secured a steel disc on whose periphery was milled a number of equally-spaced slots, and mounted above in close proximity was an electromagnetic pick-up which

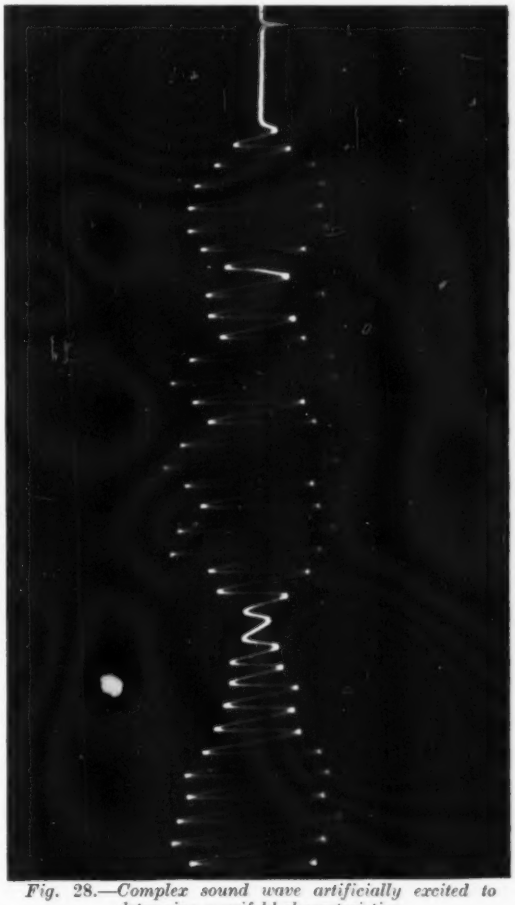


Fig. 28.—Complex sound wave artificially excited to determine manifold characteristics.

generated an E.M.F. every time a slot passed beneath the pole piece, thus affecting the flux density of the air gap. The resultant signal was amplified and passed on to the horizontal deflection plates of the cathode-ray tube. The spot motion and relative amplitude were therefore a function of disc speed and were recorded on the sensitised emulsion. The camera was designed to carry 100 ft. of recording film or paper, which was fed through the camera gate at uniform velocity immediately behind the lens. A clutch mechanism is usually incorporated in commercial designs to permit the motor to run up to speed without imparting motion to the film. There is usually some form of shutter in front of the lens which is opened in the same manner as in the case of the drum camera already described.

More elaborate cameras will include a gear-box driven by a three-cone V belt thus giving a wide choice of film speeds; naturally a refinement of

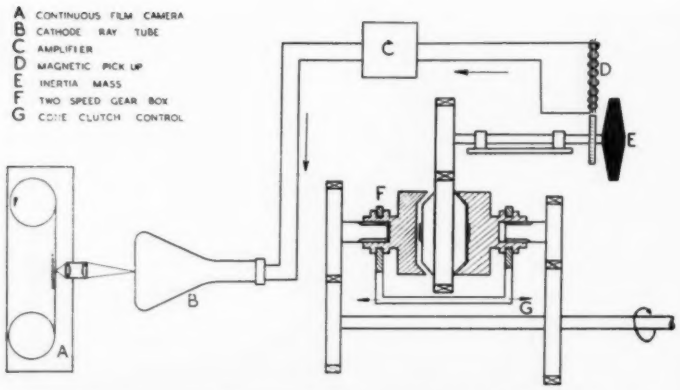


Fig. 29.—Continuous film recording to determine degree of clutch slip on two-speed gear box during acceleration.

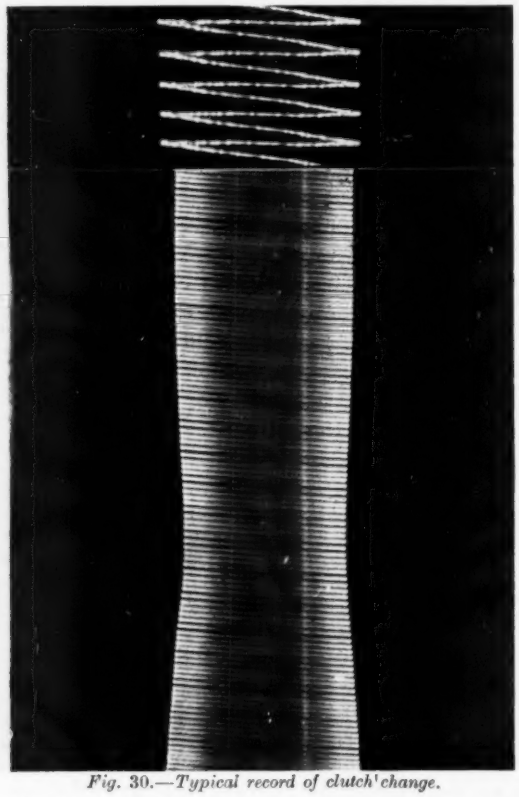


Fig. 30.—Typical record of clutch change.

this nature is very convenient but by no means essential. The fundamental requirements of both the drum and continuous film camera are so simple that for experimental work they can often be constructed in the laboratory at no great expense, the lens usually being the most costly item. In order to record the momentary speed fluctuations due to the slipping of the clutch it was only necessary to bring the rig up to speed, set the camera in motion, operate the clutch and shut down. Assuming no electrical defect the film should have recorded the motion of the spot during the process, and after subsequent development the relative amplitudes of different sections of the trace could be compared. As the amplitude is directly proportional to the rate of change of flux density in the air gap it is possible to obtain quantitative observations. A typical trace is shown in Fig. 30. The surging effect caused by the slip will be evident in the wave form of the envelope, the narrow band corresponding to the low speed section, and the wider band to the high speed. The gradual increase from one band to the other is the period of acceleration, note also the 50-cycle calibration strip.

Observations of this nature enabled the performance of various clutch designs to be compared and in this way the continuous film camera became a very important piece of equipment in conjunction with this experiment.

In conclusion it will be appreciated that the examples discussed have been selected from a number of various categories, but do not attempt fully to cover the subject. It is hoped, however, that the treatment given will illustrate the importance of photography as a well-developed research instrument which is capable of taking its place with well-established methods of instrumentation. Secondly, it is indispensable as a means of recording and whether or not the emphasis is on photography, the part it plays is vitally important.

The foregoing examples have been selected from a number of extensive engine research programmes in which the photographic technique has provided much valuable data. In view of the growing importance of this subject it is hoped that the examples given will stimulate the use of the camera and the photographic plate in the solution of engineering problems. The author wishes to express his thanks for the assistance given by members of various departments of D. Napier & Son in preparing this paper and for permission to use certain photographs.